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Petrology of the Grimstad Granite

II

Petrography, Geochemistry, Crystallography of Alkali Feldspars and Genesis

By

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Abstract

The Precambrian Grimstad granite, South Norway, has been studied by petrographical, chemical and x-ray crystallographical analysis. It has a semi-circular outline and is partly rimmed by an agmatite. Eight different rock types are found within the granite, but the chemical variation trends mostly form concentric patterns. Extreme K/Rb ratios are found in some samples, that may have been derived from charnockitic rocks (arendalites). The alkali feldspars are triclinic, but random disorder x-ray patterns and monoclinic phases — indicative of assimilation and rapid growth of alkali feldspars — are occasionally found.

The granite seems to have formed by partial melting of a granulitic substratum and the amount of granitic melt in the emplacing granite magma may have been relatively small. The different rock types have formed by more or less intense granitization of foreign material, and the granite seems to have intruded by buoyancy.

INTRODUCTION

The techniques applied to granite studies have changed several times during the period of modern petrology. A new field was opened when it first became possible to make larger number of chemical determinations rapidly by means of instrumental analysis. This development led from analyzing a few "typical" samples to treating masses of data numerically, thus giving a broader basis for discussing granite problems from a chemical and mineralogical standpoint.

The present work is a study of a deep mesozone granite employing a number of different techniques. A considerable part of the work consisted of evaluation and testing data processing methods. In the present paper, therefore, much emphasis has been put on methods and their application to granite studies, and the Grimstad granite samples served as a convenient material for the application of the preferred methods. Some studies (trace elements and single crystal x-ray work) have been based upon selected parts of the total material because of time restrictions.

A large number of the samples of the present study have been collected according to a grid point system, thus facilitating the trend surface analysis which was carried out mainly after Whitten (1961 a). Virtually all systems of sampling are open to criticism either from the standpoint of statistics or from general field experience considerations, but for most problems grid sampling clearly represents a definite improvement over the earlier practice of basing general conclusions upon data obtained from a few and selected samples.

Apart from collection of rock samples and remapping of the granite contacts, this has been essentially a laboratory study. Our data have been collected from macroscopical and microscopical examination of slabs and thin sections, chemical analysis of whole rock samples and, in certain cases, of the feldspars which they contain, and X-ray diffraction studies of the alkali feldspars.

In the present paper we shall present observations that lead us to believe that the Grimstad granite originates from a substratum near the border between the rocks of the amphibolite facies and the granulite facies affinities and was emplaced under "minimum melt conditions" as a magma consisting of melt and solid components. The solid components of the magma were consistently recrystallized. The basic inclusions, virtually insoluble in a granitic melt of minimum melt composition, show all gradations from fresh looking amphibolites to ghost like xenoliths, inferring that they have been assimilated not by dissolution in a silicate melt but by transport of material through an intergranular vapor phase. Such transport of material has been demonstrated experimentally by several authors (e.g. Orville, 1962) and the X-ray crystallographic data of the alkali feldspars support this hypothesis.

GENERAL GEOLOGY

Geological setting.

The Grimstad granite is situated in the Bamble area in South Norway, just to the north of the town of Grimstad ca. 50 km NE of Kristiansand (Figure 1). The rock province of the Bamble area is characterized by banded gneisses often granitized and sometimes carrying sillimanite, amphibolites ranging from apparent derivatives of basalts or gabbros to tourmaline bearing metasediments, quartzites, pegmatites of several different types, gabbroic intrusions rimmed and often interpenetrated by scapolite-amphibolite rocks, and intrusive granites, like the Herefoss and the Grimstad granite. Oftedal (1938, 1945), Bugge (1940, 1943), Elders (1968), Heier (1962) and Smithson (1963 a) have contributed to the description of the Grimstad granite and Christie, Falkum, Ramberg and Thoresen (1965) gave a progress report on the present study. A general survey of the Bamble area, including the Grimstad granite, is given in Barth and Reitan (1963).

In his study of the Bouguer anomaly of South Norway, Smithson (1963 a) demonstrated the existence of a marked half circular pattern above the Grimstad granite. Smithson interpreted this to mean that the Grimstad granite is a funnel shaped body and extends about 2 km below its present surface. It is separated from the nearby Herefoss granite by a 10 km wide band of Precambrian gneisses. The age of the Grimstad granite has not been accurately determined, and the data reviewed by Broch (1964) indicating an age of about 900 m.y. must be considered provisional, but it seems justified to propose a Precambrian age for the Grimstad granite.

The depth of intrusion and consolidation of granites has been given widely different values; Tuttle and Bowen (1958) suggest 9 miles or less, whilst Gutenberg's (1957) estimate is 35 miles. Following the nomenclature of Buddington (1959) the Grimstad granite is a deep mesozone granite emplaced at a depth around 8—10 km.

The terrain around Grimstad is smooth with rounded hill tops and fertile soil. At the coast the red colour of the granite is so typical that it serves as a navigation sign. The rocks are usually fresh, with a weathering skin commonly less than 2 mm thick.

A series of subparallel dislocation zones determines both the trend of the coastline and the main valley pattern. One of the most

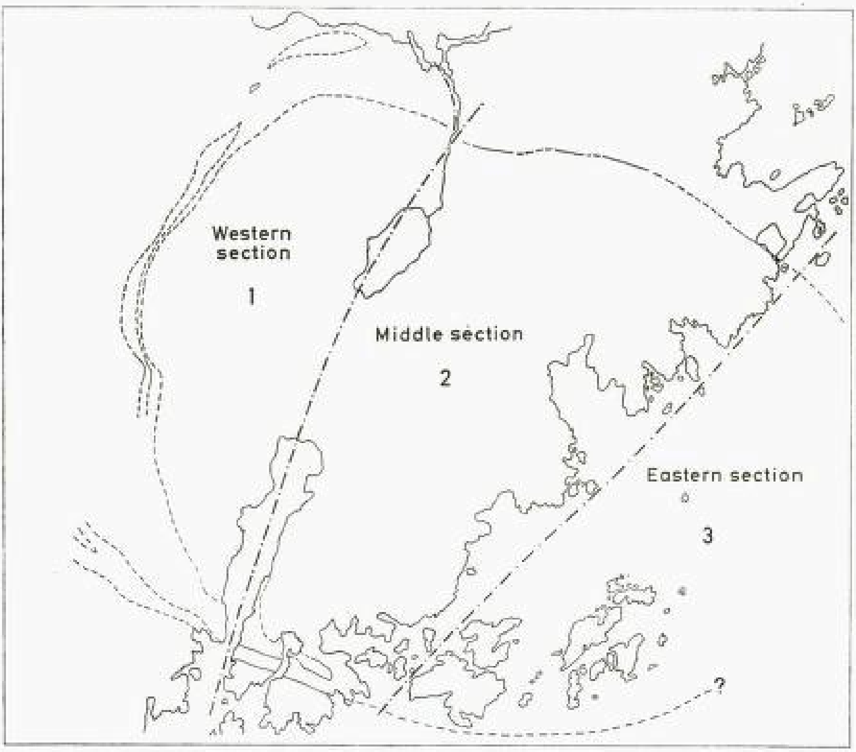

Figure 2. The Grimstad granite is cut by two dislocation zones that divide the granite body into three sections.

conspicuous topographic features is the valley formed in the Vikskilen dislocation zone which is now largely filled by lake Temsevann. To the north and southeast of Temsevann fluorite crystals may be observed. A Quaternary moraine overlies parts of the granite and forms hills at several places in the landscape.

The granite has been subject to occasional quarrying, and earlier pegmatite quarrying has also taken place, although there is a notable scarcity of pegmatites in the Grimstad granite.

The Vikskilen and the coastal fracture zones divide the granite into an eastern, middle and western section as shown on the sketch map (Figure 2). The regional trend of the foliation of the country rocks is parallel to the fracture zone and the coast line, and the minor fractures in the granite, mostly joints, are either parallel to the coast or roughly parallel to the granite border.

The granite border of the middle section is sharp, we have observed no agmatite zones, but numerous smaller pegmatites occur in the gneiss areas between Vikskilen and the coast. The foliation of the country rock is mostly perpendicular to the border, but in the Kvikshaug area there is a tendency of blockwise breaking up of the country rocks. The blocks have been rotated so that the foliation becomes subparallel to the granite border. This zone is about 100 m broad at

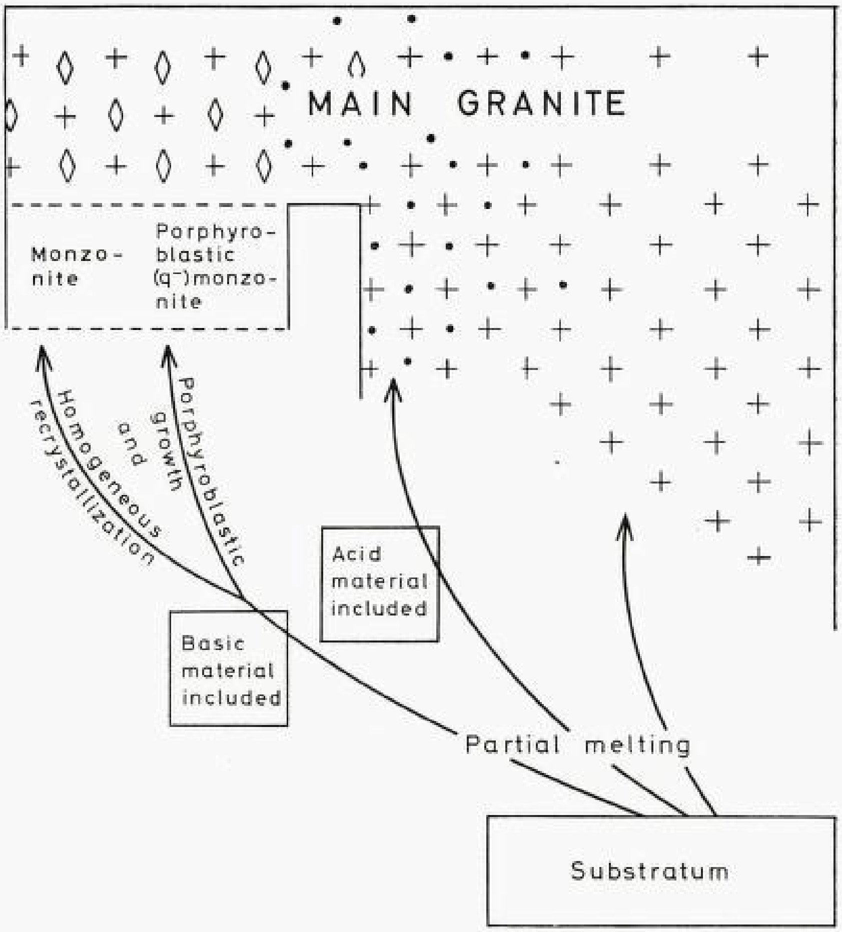

Figure 3. Display of petrogenetic processes leading to the different rock types within the Grimstad granite. Porphyroblastic transitions into granite marked by rhombs, porphyritic transitions by dots.

Kvikshaug and pinches out towards Birketveit. The discordant nature of the granite border has been recorded by Oftedal (1938, 1945), Bugge (1940, 1943), Barth (1960), Taylor and Heier (1960), Elders (1963) and Smithson (1963).

The granite border of the western section is characterized by an agmatite zone, and the foliation of the country rock is mainly concordant to the granite border. The agmatite zone is 50—600 m thick and pinches out at Kvikshaug. It consists of angular and subangular inclusions of gneisses and amphibolites in a medium grained greyish to pink granitic groundmass. The agmatite zone grades into normal granite as the grain size of the ground mass increases and the inclusions become less frequent and more thoroughly assimilated.

In the eastern section, the agmatite at Vaholmene contains large inclusions of well preserved gneisses and amphibolites. There is thus little doubt about the origin of some of these angular inclusions. They represent xenoliths derived from the country rocks and they are often rotated in relation to the prevailing foliation outside the granite.

Rock types.

A wide band of monzonitic rocks — the "dark facies" rocks of Oftedal — occurs along the coast from Søm to Moisanden where it bends to the west and passes over to Vikskilen. This area is characterized by the presence of dark inclusions, some of considerable size, with more or less sharp contacts towards the monzonitic rocks that may be of porphyroblastic character. Scattered occurrences of monozonitic rocks are also found elsewhere in the Grimstad granite.

The subdivision of rock types in the Grimstad granite is given in Table I, their genetic interrelations are given in the sketch of Figure 3.

Table I. Rock types of the Grimstad granite:

Normal granite	Main granite
Medium grained granite	
Fine grained granite	
Aplitic granite	
Agmatite	
Porhyritic granite	
Porhyroblastic (quartz) monzonite	Dark types
Non-porphyroblastic monzonite	

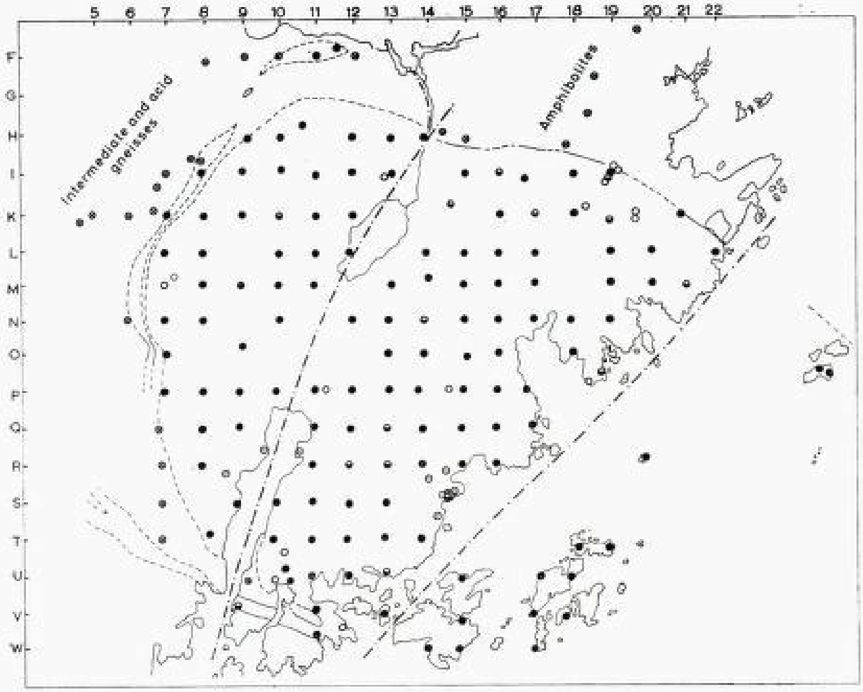

Figure 4. Sample stations: Filled circles = main granite, half filled circles = monzonite and porphyroblastic (q-) monzonite, open circles = main granite samples outside the grid point sample stations, circles with dot = monzonite and porphyroblastic (q-) monzonite samples outside the grid point sample stations, crossed circles = samples outside the Grimstad granite.

Obvious signs of contact metamorphism along the granite border have not been observed by us. The country rocks are often cut by granitic dikes, but these are common in the whole Bamble area, and with one notable exception, mentioned in the following paragraph, we have not been able to demonstrate that any of these dikes or veins have come from the granite itself, although larger blocks of amphibolite in the agmatite zone seems to have been penetrated by fine grained granitic veins after their inclusion in the granite. At the south border, field observations indicate that recrystallization of granitic bands within the country gneiss may have taken place during the emplacement of the granite, but the observations are not unambiguous.

In the western banded gneiss complex of the mapped area a 50—200 m wide granite dike runs parallel to the border of the Grimstad granite. Smaller elongate lenses of a similar fine grained granite is located to the north of the Grimstad granite. These granites may be part of a discontinuous cone sheet which could have been fed from the Grimstad granite itself. This may be studied at the Hesnes peninsula where a large granite apophysis turns gradationally into aplite. A possible continuation of this apophysis runs through the town of Grimstad.

PETROGRAPHY

Description.

The normal granite.

The typical coarse grained to porphyritic normal granite occupies most of the surface of the granite body. It can be studied in fresh and splendid road cuts along the main road (E 18) and other roads within the granite. Except for the varieties described below the granite has a rather uniform appearance throughout.

The normal granite has a characteristic pink to red colour, owing to elongate or tabular microcline megacrysts measuring from 1 to 5 cm. These microcline megacrysts constitute the main mineral phase, whilst the matrix consists of plagioclase, varying in composition from albite to andesine, quartz, biotite and chlorite. Accessory minerals are apatite, epidote and allanite, hematite, ilmenite, magnetite, pyrite, muscovite, zircon and sphene, and occasionally fluorite and calcite.

Modal analysis shows that the minerals of the normal granite samples vary quantitatively within wide ranges (Figure 5, Table II) but still the standard deviations of the modal minerals are small, except for alkali feldspar. The normal granite as a whole is, following Streckeisen (1967), classified as a *granite* (Figure 6). It should be noted, however, that the granite fields of Streckeisen is identical with both the granite and the quartz-monzonite subfields of Trøger (1961), Bateman et al. (1963) etc. or the granite or adamellite subfields of for example Williams et al. (1958). Following the latest proposal by Schreyer and Walger (1967) the Grimstad granite might be subdivided into syenogranite and monzogranite, the latter being the most common type.

The large pink to red phenocrysts of microcline perthite are almost always fresh in thin section. They show almost invariably inversion twin pattern; occasionally, however, the M-twins are feebly or patchily

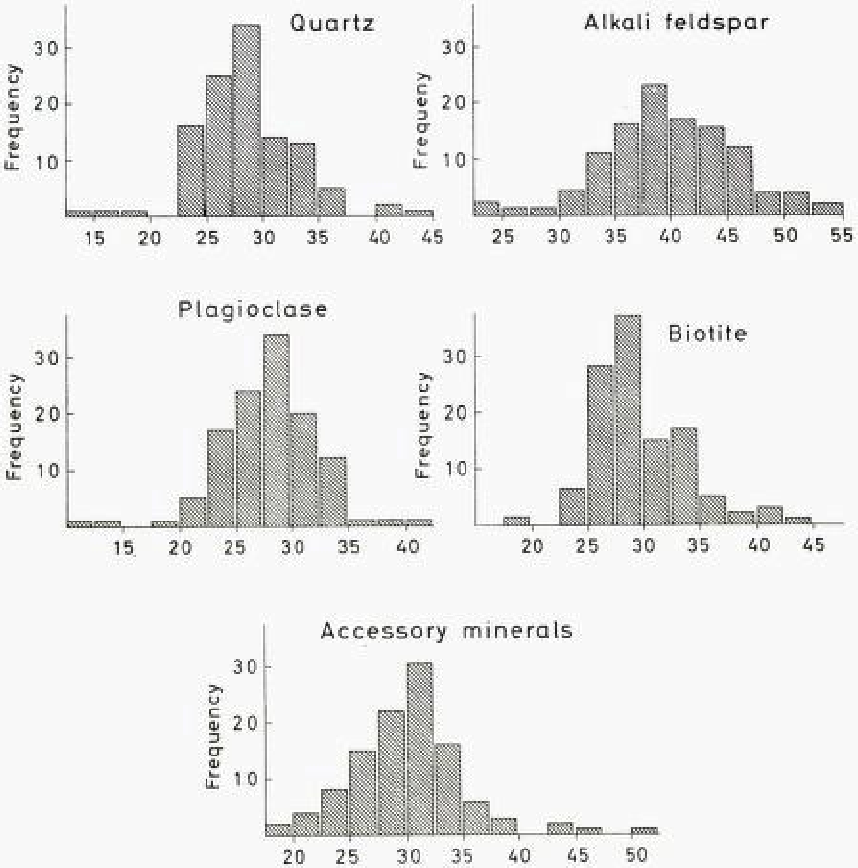

Figure 5. Frequency distribution of the minerals of main granite samples.

developed. The types of perthite correspond to macro- and microperthite, possibly also cryptoperthite.

The macroperthite has irregularly shaped albite patches grading into ordinary albite veins with a thickness of 0.5—2 mm. Less coarse macroperthite albite lamellae oriented subparallel to (001) have been observed, they apparently correspond to plate perthite (Laves and Soldatos, 1962 a).

Microperthitic albite lamellae developed as 0.005 mm thick films are roughly parallel to the vein perthitic albite lamellae of the same crystal. The angle with the (001) cleavage in the (010) sections is 106—108° for the microperthites and 107—117° for the macroperthites (see

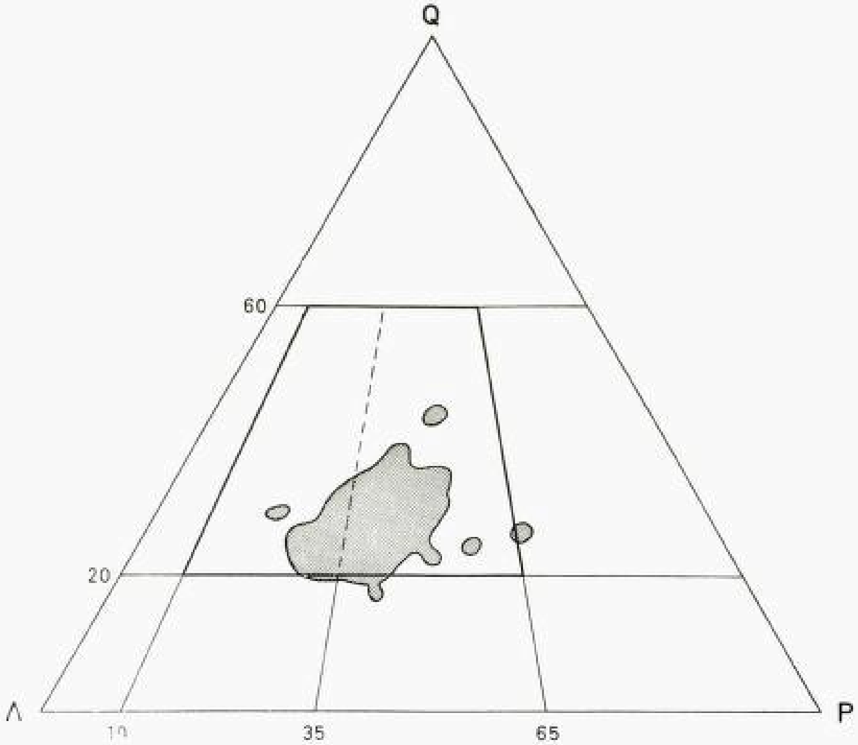

Figure 6. QAP diagram of the main granite samples with granite field of Streckeisen (1967).

Laves and Soldatos, 1962 b). X-ray crystallographic properties of perthite samples are given on pages 54—58.

The frequency of Ab lamellae increases generally towards the center of the larger alkali feldspar crystals. Sometimes an increase in M twin lamellae size towards the center is observed as well. This distribution can probably be explained on the basis of difference in structural state, the edges being less Al/Si ordered than the center. Ordinary M-twins may even be poorly developed in the central part.

At the contact with plagioclase crystals the alkali feldspar may be almost free from albite lamellae, whereas the plagioclase crystal has developed an albite rim, indicating that the albite component have migrated out of the alkali feldspar and mantled the plagioclase.

Subhedral or rounded microcline megacrysts are often rimmed by plagioclase having the same optical orientation and continuing into

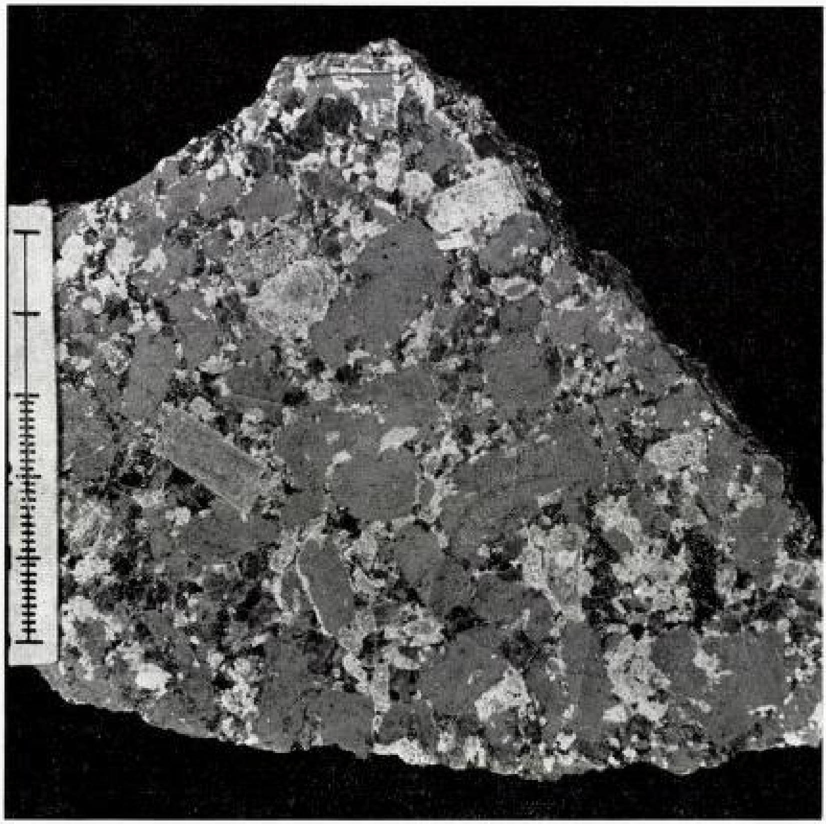

Figure 7. Stained slab of Grimstad granite. White = plagioclase, light grey = alkali feldspar, dark grey = quartz and accessories. Length of scale is 5 cm, sample station N 15.

the albite lamellae. Plagioclase may also be encased by alkali feldspar, and complex megacrysts built up by alternating plagioclase and alkali feldspar zones are not uncommon. Normally and inversely mantled feldspar crystals are found together with nonmantled euhedral alkali feldspar crystals in the same hand specimen (Figure 7).

This mantling of the feldspar crystals is very common and gives the rock a rapakivi-like texture which is even better developed in the porphyritic and porphyroblastic varieties. Inclusions of quartz and plagioclase in the alkali feldspar crystals are common and may occasionally show parallel orientation throughout the thin section. Irregularly shaped plagioclase clouded by alteration products occurs as diffuse cores in alkali feldspar crystals while fresh microcline and quartz are present as patches in the plagioclase crystals, both phenomena indicative of replacement of plagioclase by alkali feldspar.

Plagioclase occurs either as euhedral to subhedral normally zoned crystals up to 0.5 cm in size, or as aggregates composed of several small anhedral crystals. The core of the larger crystals is altered and sericite has been identified as one of the alteration products. The plagioclase crystals occurring in aggregates are fresh and clear.

We consider it an important observation that the altered, large crystals have a core composed of An_{28-33} and a rim composed of An_{18-30}, and that the smaller, clear plagioclase crystals are mostly albite with compositional range An_{3-15}. Even though they may have compositions ranging into acid oligoclases the latter will be referred to as albites in the following discussion to distinguish them from the coarser, altered oligoclases. Albites with different optical properties occur side by side in the aggregates. It is not known whether this is a result of differences in chemical composition or in thermal state. Quite small changes in either of these parameters result in a measurable change in optical properties.

Quartz occurs either as rounded aggregates consisting of several crystals of different optical orientation, or as single euhedral or rounded crystals ranging up to 4—5 mm. The rounded crystals are sometimes surrounded by a rim of femic minerals, often easily seen even in hand specimen. Macroscopically the large quartz crystals often have dark blue or greyish blue colour, but the light grey colour dominates. The quartz crystals have undulatory extinction and carry inclusions of various minerals.

Biotite is found in minor amounts. It is generally altered to chlorite along margins, cracks and cleavage planes. The common absorption colours are light yellow (X) and brown (Z). Biotite is often associated with sphene and ore, and commonly contains minute grains of zircon with pleochroic haloes. Fluorite, and more rarely calcite, may be locally intimately intergrown with biotite.

Helsinkite

Helsinkite occurs as a local variety of the main granite in a road cut south of Steinstjern. It is easily recognized because of its heavily weathered surface and its pink-green-blue colour. It consists of the

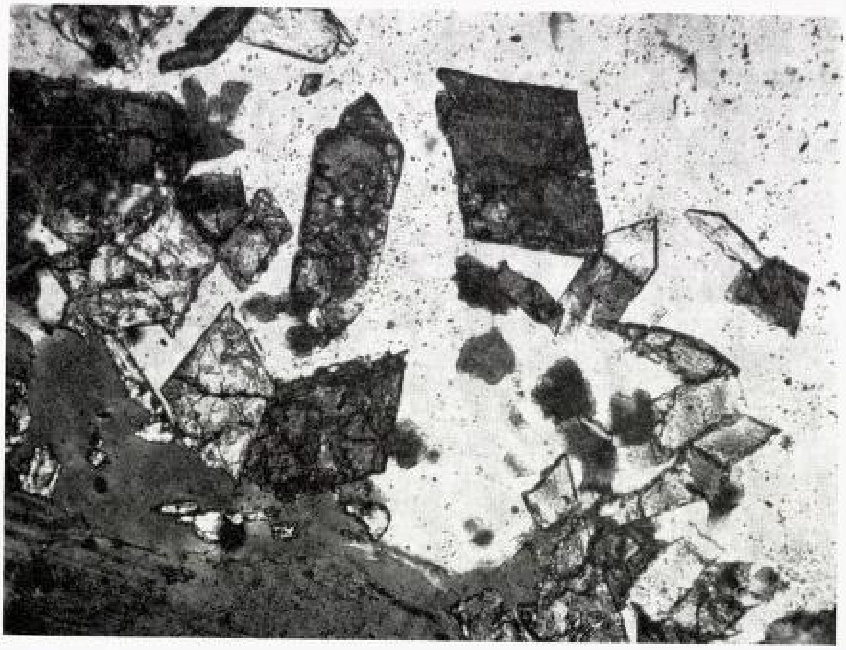

Figure 8. Thin section of helsinkite, showing euhedral crystals of epidote together with alkali feldspar and plagioclase. Magnification 30 x, sample station L 8.

ordinary pink microcline perthite, greyish blue quartz, albite-oligoclase, chlorite and epidote, that is to say the mineral content of the main granite plus epidote.

The idiomorphic 1—3 mm long epidote prisms are evenly distributed throughout the thin sections and are usually associated with plagioclase. Epidote occurs as inclusions in alkali feldspars as well and is clearly formed at an earlier stage than both alkali feldspar and chlorite (Figure 8). The epidote has not the character of a secondary mineral.

According to Laitakara (1918) helsinkite is a magmatic rock where epidote is supposed to have been precipitated from the melt. We have not studied thin sections of his rock, but from the description epidote seems to occur in a manner similar to that of the helsinkite variety of the Grimstad granite.

Medium grained granite

The medium grained granite is found mainly in the western agmatite zone and on a few localities in the central part of the Grimstad

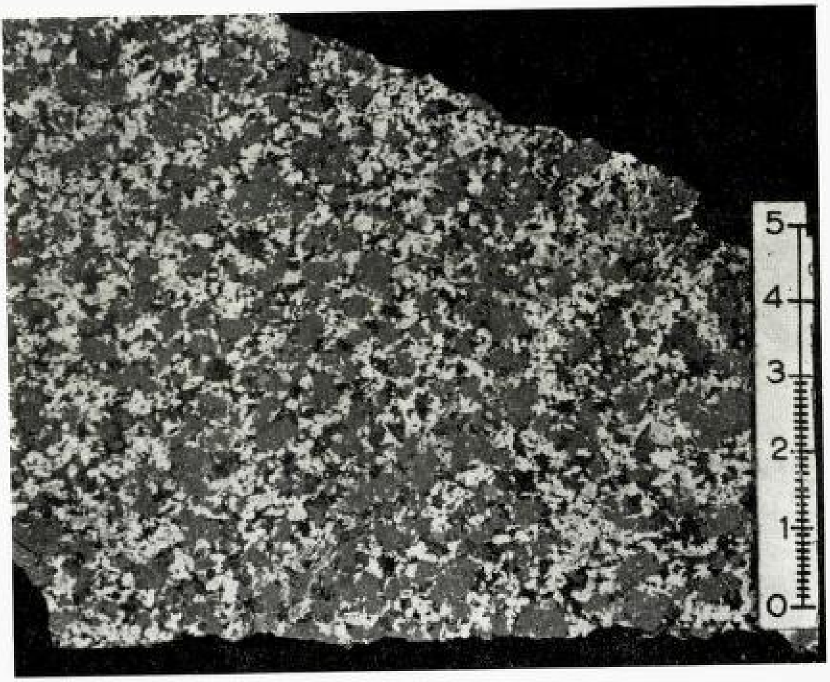

Figure 9. Medium grained granite, stained slab. White = plagioclase, light grey = alkali feldspar, dark grey = quartz and accessories. Length of scale is 5 cm, sample station S 9.

granite (N12, N13, P13). It may change gradually into normal granite, and in the western agmatite zone it usually represents a transitional stage between the fine grained granites and the normal granite.

The grain size is approximately 3—5 mm with somewhat larger crystals of alkali feldspar that may be up to 10 mm (Figure 9). A faint orientation of the feldspars parallel to the boundary is sometimes seen.

The alkali feldspar is a microcline perthite with different sets of albite lamellae. Most abundant is the film perthite with thin films, 0.02—0.1 mm long and about 0.005 mm thick, oriented normal on the (010) plane and with an angle of approximately 75° to the (001) cleavage. This type is most perfectly developed in the finer grained varieties of the medium grained granites. With increasing grain size the films also increase in size and their contours become diffuse. At this stage appears the vein perthite which is so abundant in the normal granite.

The plagioclase is sericitized, particularly in the core. Extinction measurements indicate an An content of 24—32. Myrmekite is common.

Other minerals are biotite, chlorite (chloritized biotite), muscovite, sphene, apatite, epidote, ore and small zircon grains in biotite. Some thin sections also have small amounts of calcite and fluorite, the last may be found as lamellae in biotite.

Mineralogically the medium grained granites are very similar to the normal granite (Table II). There is a tendency towards lower alkali feldspar/plagioclase ratio in the medium grained types, possibly indicating contamination by more basic country rocks.

Fine grained granites

The fine grained granites occur in three different ways:

1: As dikes, crosscutting the main granite and the monzonites and porphyroblastic (quartz)-monzonites.
2: As larger bodies in the western agmatite zone. These fine grained types are often foliated and show gradual transitions into the medium grained granite.
3: As single bodies to the north of the Grimstad granite. The genetic relationship between these bodies and the main granite is uncertain. Geographically they form a continuation of the outer agmatite zone, but textural differences, particularly in the perthites, make a genetic relationship doubtful.

In hand specimen their grain size is 1—2 mm and in contrast to the aplites the different minerals are clearly discernible. The alkali feldspar is usually reddish, the plagioclase grey or greyish white, and the quartz grey. The grain size is uniform within each specimen, i.e. there is no tendency towards porphyroblastic texture.

The alkali feldspar is a microcline perthite with varying amounts and types of exsolved albite lamellae. The dikes and the larger bodies carry film perthites of the same types as described under medium grained granite (Figure 10). The amount of albite component, estimated in thin section, is about 5 %. The perthites of the largest single body to the north of the Grimstad granite differ by having approxi-

Figure 10. Film perthite of fine grained granite sample, section roughly parallel to (001). Magn. 120 x.

mately 20 % of exsolved albite lamellae, estimated in thin section. These lamellae are larger, 0.2—0.5 mm long and 0.3 mm thick with a flame-like appearance. The coarse vein perthites typical of the normal granite, have not been found in the fine grained granites.

The plagioclase is strongly sericitized, particularly in the core, and the crystals often have a fresh, albitic rim. It has not been possible to measure the An content of the plagioclases accurately in thin section, but chemical analysis of the plagioclase fraction of one fine grained sample (R 14fg) gives the value An_6. Myrmekitic textures are common, and the dark minerals are chlorite, probably formed from biotite, and muscovite, accessories are sphene, apatite, epidote and magnetite.

Table II shows that the modal compositions of these granites are rather similar to the modal compositions of the normal granite samples. The alkali feldspar/plagioclase ratio is lower, however, than in the normal granite, showing the close relationship between some of the fine grained granites and the medium grained granites.

The table of modal analyses (Table II) shows that the standard deviation for alkali feldspar and plagioclase is large compared with that observed among the normal granites, indicating that the fine grained granites do not constitute a petrographically homogeneous group of rocks. This, together with their varying modes of occurrence indicates that we are not dealing with rocks of common origin. The more plagioclase rich types are probably due to contamination by basic rock types and/or plagioclase gneisses in the country rocks, whilst the types richer in quartz and alkali feldspar may be related to the aplites or possibly to the granitic gneisses of the country rocks in the west.

Aplite

The aplites occur in two different ways:

1: As dikes, crosscutting both the normal granite and the monzonites and porphyroblastic (quartz)-monzonites.
2: As a large body at Rønnes in the southern part of the granite, which grades eastwards into the normal granite type. This same aplite possibly reappears at the western side of Vikskilen, branching out into the covered area towards the northwest.

On the basis of mineral composition and field relations we have called these rocks aplites. They are more fine grained than the other leucocratic rocks of the Grimstad granite and they carry very little dark minerals. The grain size is usually less than 2 mm. Both the alkali feldspar and the plagioclase is red and this gives the aplite a uniform appearance in contrast to the fine grained granites where the two types of feldspars are easily distinguished in hand specimen. There seeems to be no sharp division, however, between aplite and fine grained granite.

The alkali feldspar of the aplites is microcline occurring in anhedral grains, non-perthitic or weakly perthitic. The perthite is a film perthite with albite films 0.02—0.05 mm long and 0.005 mm thick, oriented normal to (010) and with an angle of either 83° or 70° to the (001) cleavage.

The subhedral plagioclase grains are strongly sericitized, and for this reason the optical measurements of the An content are uncertain, but the chemical analysis of a separated plagioclase fraction from one aplite (V 8—1) indicates that it is an almost pure albite (An_4). Sericitized plagioclase remnants are often found as cores in fresh alkali feldspar.

Muscovite is the dominating mica, only traces of chloritized biotite have been found. Accessories are calcite, epidote, fluorite and magnetite.

From Table II it is seen that the aplites are characterized by a high quartz content and a low content of dark minerals. Compared to the normal, medium grained and fine grained granites, the alkali feldspar/plagioclase ratio has increased considerably.

Assuming normal magmatic differentiation, the aplites may be regarded as late differentiates, a view supported by the high Rb content (page 47).

The large aplite body at Rønnes may also be interpreted as a recrystallized quartz-feldspar gneiss with mineralogical and geochemical characteristics inherited mainly from the original gneiss. However, the sharp crosscutting boundaries to the country gneisses and amphibolites, and the lack of similar aplites in the strike direction makes this interpretation less likely.

Porphyritic granite

A porphyritic variety of the normal granite is found in restricted areas and almost always associated with the darker rocks described below. On the island of Ryvingen only porphyritic granite occurs.

The porphyritic granite shows gradational border relations towards the normal granite, while the porphyroblastic and darker rock types may be observed as subangular inclusions. These inclusions, however, have rather diffuse borders, sometimes more than half a meter wide.

Modal analyses (Table II) show that the porphyritic variety, although clearly more basic than the normal granite, is still within the granite field of Streckeisen (1967) or monzogranite subfield of Schreyer and Walger (1967). The microcline phenocrysts, up to 5 cm long, occur in a matrix slightly more femic than the normal granite.

The subdivision into normal granite, porphyritic granite, porphyroblastic (quartz) monzonite and non-porphyroblastic monzonite is useful in the field. It must be stressed, however, that there is a continuous mineralogical and chemical gradation from the dark rock types through the porphyroblastic and porphyritic varieties into the normal granite. In thin section the porphyritic granite is seen to contain the same mineral assemblage as the normal granite, it is only the relative proportions which vary.

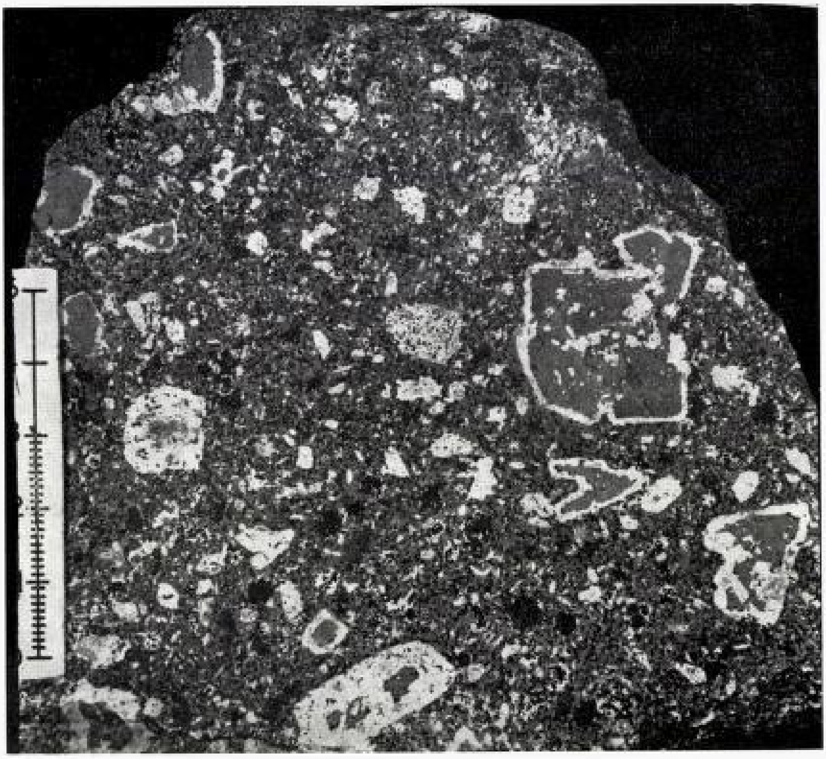

Figure 11 a. Porphyroblastic q-monzonite, stained slab. White = plagioclase, light grey = alkali feldspar, dark grey = quartz, biotite and accessories. Length of scale is 5 cm, sample station S 15—32 b.

Porphyroblastic (quartz)-monzonite

The porphyroblastic rock types are local varieties of the monzonite described below, with which they are always associated. As seen from Figure 1 the darker rocks are found at several widely separated localities within the Grimstad granite, the porphyroblastic varieties, however, may best be studied at Haukenes and Moisanden.

The porphyroblastic varieties contain both dark inclusions and dikes or irregular bodies of aplite. The porphyroblastic rock types have a dark to reddish grey appearance and contain megacrysts of microcline perthite and sometimes rounded quartz. With increasing numbers of megacrysts the porphyroblastic varieties grade mineralogically into the less femic varieties described above. Between the porphyroblastic and

Figure 11 b. Coexisting mantled plagioclase and alkali feldspar. Section 4 cm across, sample station N 14.

non-porphyroblastic femic varieties there is also a complete mineralogical gradation. From the modal analyses (Table II) the intermediate composition of the porphyroblastic varieties relative to the porphyritic granite and the monzonite is clearly seen.

The megacrysts are often composed of alkali feldspar with a plagioclase rim, but plagioclases with alkali feldspar rims also exist (Figure 11 a and b). For further thin section petrography the reader is referred to the non-porphyroblastic monzonite described below.

Monzonite

The monzonitic rock types (Table II), easily distinguished in the field from the granite because of their light or dark grey colour, are widely distributed in the Grimstad granite, but are most common in the middle section from Vikskilen to Moisanden and northwards along the coast to Haukenes.

In the large monzonitic areas where the rocks are coarse grained and equigranular, the borders against granite may either be gradational over several tenths of meters or, more rarely, quite sharp. Crosscutting aplitic dikes are commonly associated with these monzonites.

The fine to coarse grained fragments of dark rocks of monzodioritic to quartzmonzonitic composition often have a rim of porphyroblastic quartz monzonite. This rim may again have either sharp contacts with the surrounding rock or a border zone gradually changing from porphyroblastic quartz monzonite via porphyritic granite into the normal granite.

In the agmatite zone angular monzonitic rock fragments occur together with fragments of country rocks. These blocks have commonly been rotated as seen from their foliation, which shows varying degree of preservation. The fractures of these blocks are commonly filled with fine grained granitic material.

The dark rocks carry more plagioclase and biotite and less quartz and alkali feldspar than the normal granite (Figure 12). The darkest types may carry amphibole and pyroxene, possibly inherited from the country rocks amphibolites and arendalites. No lineation or foliation occurs in the monzonitic rock types. Texturally these rocks are further characterized by lath-shaped plagioclases. The plagioclases are sericitized, often more strongly in the center. In some cases the plagioclases carry a rim either of alkali feldspar or of albite. The monzonites as well as the quartz monzonites often show a rapakivi-like texture more pronounced than that of the normal granites.

Fresh idiomorphic albite and oligoclase crystals (An_{3-15}) are most often associated with alkali feldspar porphyroblasts in the dark types.

Crosshatched microcline and more rarely orthoclase are found as porphyroblasts and as interstitial fillings. The larger crystals are often sub- to euhedral. Quite a few grains exhibit poorly developed crosshatching, particularly in some of the more basic rocks.

The microcline is commonly perthitic and different types of albite lamellae may be encountered even within a single grain. Occasionally two sets of albite veins cross each other, the perthite with the thinnest and most regular veins seems to be the latest formed. Patch and vein perthites are the most common types, although film perthites may be found quite frequently. Patch perthite is common in the larger micro-

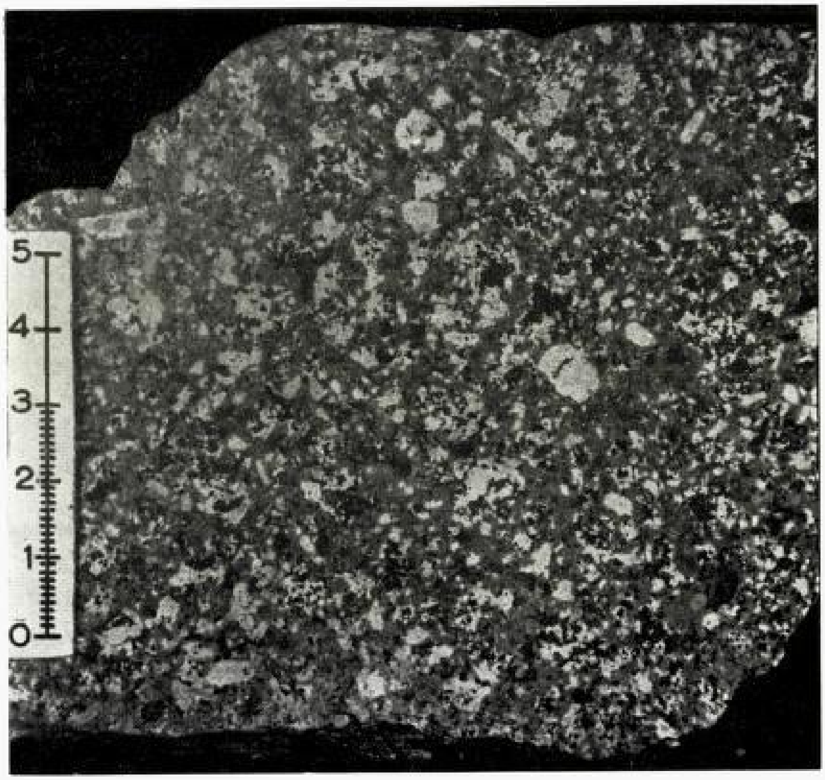

Figure 12. Monzonite, stained slab. White = plagioclase, light grey = alkali feldspar, dark grey = quartz, biotite and accessories. Length of scale is 5 cm, sample station S 14—14.

cline porphyroblasts, especially in connection with replacement of plagioclase. Faintly twinned and strongly sericitized plagioclase grains may grade into ordinary patch perthites. These patches may be very irregular and also sericitized. Vein and film perthite, together with patch perthite, may occur in the same porphyroblast.

The 2—5 cm large microcline porphyroblasts are usually built up of a single or a few crystals. Plagioclase grains are frequently included together with minor amounts of the accessory minerals. Some of the plagioclase inclusions are euhedral, fresh crystals of composition An_{5-20}, others are sericitized and these always seem to be more basic in composition. In quite a few crystals there is a densely sericitized core surrounded by a fresh and more albitic rim, features which indicate that plagioclase more basic than An_{20} was unstable during the growth of the microcline porphyroblasts, and that the fresh and acid plagioclases have developed during the latest crystallization.

The sericitized plagioclases sometimes contain chessboard albite, and may be surrounded by thin, irregular lenses of quartz and calcite. In some cases calcite appears to have formed as a secondary product during replacement of plagioclase by microcline.

Myrmekite is frequently found at the margins of the porphyroblasts, and the content of biotite and amphibole is higher close to a porphyroblast than elsewhere in the matrix.

The quartz crystals, which are mostly anhedral with strong undulatory extinction, often occur as irregular grains interstitial to the feldspars. Spheroidal quartz aggregates or single crystals, 3—10 mm in diameter, sometimes occur within the basic matrix. They are almost invariably surrounded by a dense rim of mafic minerals, indicative of porphyroblastic growth.

The biotite is pleochroic (Z = dark green, Y = light green), the crystals are bent and may be altered to chlorite. Alteration is common along fringes and cleavage planes, and fluorite occurs as thin lenses within the biotite crystals.

The more basic rock types have coexisting pyroxene and hornblende; either poikilitic hornblende (Z = bluish green, X = light yellow), occasionally with pyroxene inclusions, or clinopyroxene and hornblende.

The dark rock types to the north of Temsevann carry randomly distributed biotite flakes together with orthopyroxene, they probably represent altered xenoliths of arendalite (described by Bugge, 1943).

Accessory minerals are apatite, calcite, chlorite, colourless mica, epidote, fluorite, sphene, zircon and opaques. These may form complex aggregates together with biotite and hornblende.

Oligoclase and andesine (An_{20-35}), biotite, pyroxene, amphibole, and sphene predate the fresh albite (An_{3-15}), alkali feldspar, epidote, colourless mica, fluorite, apatite and chlorite. Chlorite seems in most cases to have formed from biotite, epidote and colourless mica from oligoclase.

Modal analyses.

In order to investigate mineralogical variations in the normal Grimstad granite and its various subtypes, most of the grid point samples and several other specimens were subjected to modal analysis by point counting. The earliest work on areal variations in granitic massifs was based on modal analyses (Whitten 1959; 1961 a and b). Modal analyses have also been used to determine chemical composition, thus Chayes (1956) and Heier (1961) state that, for granitic rocks, a modal analysis is almost as accurate as a chemical analysis and much more economical. Barth (1959; 1962) has demonstrated good agreement between modes and mesonorms both for granites and for basic rocks with a mineral composition corresponding to amphibolite facies.

In rocks like the Grimstad granite the porphyritic texture, zonal appearance of feldspars, and frequent fine intergrowths, make the value of modal analysis as a means of determining chemical compositions more doubtful. In fact, some authors (Baird, McIntyre and Welday, 1967) even reject modal analysis as a method of recording mineralogical variations in granitic rocks, replacing the modal variations with variations in the calculated katanorm. We feel, however, that variations may best be established by taking advantage of both modal analyses and norm calculations, using in this case a *mesonorm* because of its closer agreement to the observed mineralogy.

The modal analyses were performed on etched and stained rock slabs (Bailey and Stevens, 1960), counting at least 1000 points in a "macro grid" (Fitch, 1959) with a special point counter adapted to that purpose (Smithson, 1963 c). Three factors are contributing to the errors in modal analyses: sampling, identification and counting errors. The identification error, including systematic operator errors caused by textural problems, is generally much less than the sampling and counting error. The difficulty of obtaining representative samples of a given body, the sampling error, is aggravated in this case by the coarse grain size of the granite. In the present study, however, it is not the object to obtain a modal analysis of each individual sample, but to use the results from a large number of samples examined to obtain the average mineralogy of rock types and bulk granite. The sampling error is therefore considered to be insignificant in relation to the total error. The very coarse grain size will also contribute to the counting error, since for a fixed count the ratio between point distance and grain size will obviously affect the reliability of the results. Thus Bayly (1960) presents tables that show the count area necessary for a given precision in granitic rocks, while Van der Plas and Tobi (1965 a) give a chart for judging the reliability of point counting results with a 95 percent confidence. They state that the point distance should be larger than the largest grain fraction that is to be included in the analyses in order to avoid correlated observations.

Applied to the Grimstad granite this statement implies that rock slabs as much as 0.25 m^2 may be required. This subject is, however, constantly under discussion (Chayes, 1965; Van der Plas and Tobi, 1965 b). In the case of the Grimstad granite we have made an effort to compromise between the ideal requirements and what is feasible, and to make an estimate of the resulting precision.

By choosing rock slabs offering a count area of at least 10 by 10 cm^2 the counting and sampling errors are reduced. By determining variations within one outcrop (Table IV) the maximum value of analytical (counting and identification) errors has been established. Variations less than this have not been considered. Several samples have been subjected to replicate analyses by up to four different operators, the operator bias has thereby been removed. In Table V the statistical data are given for 11 samples counted three times or more by different observers. Assuming that the granite has an approximately constant mineralogical composition, that the population (rock slabs) have a common variance, and that the modal minerals have a normal distribution, this table gives an estimate of the precision of the method. Erratically high values of the variance in N 10 and V 18 are due to identification difficulties because of intimate intergrowth textures and uneven appearance of the feldspars.

From the table it appears that alkali feldspar exhibits a much greater variance than the other chief constituents, possibly because of its irregular appearance, intergrowths and perthitic inclusions. The relatively large variance of the accessory minerals as compared to f.ex. the variance in biotite, stresses the well known fact that in modal analyses the accuracy decreases strongly for the less frequent components.

The frequency distributions of the major minerals in normal Grimstad granite (Figure 5) reveal that all the modal mineral groups have normal distribution. The normal granite samples are spread over a wide range from syenogranite through monzogranite almost to granodiorite, but the majority fall within the granite field of Streckeisen (Figure 6).

From Table II and Figure 13 it is evident that the lower content of alkali feldspar in the medium grained granite is compensated for by a higher relative content of femic minerals, plagioclase and quartz.

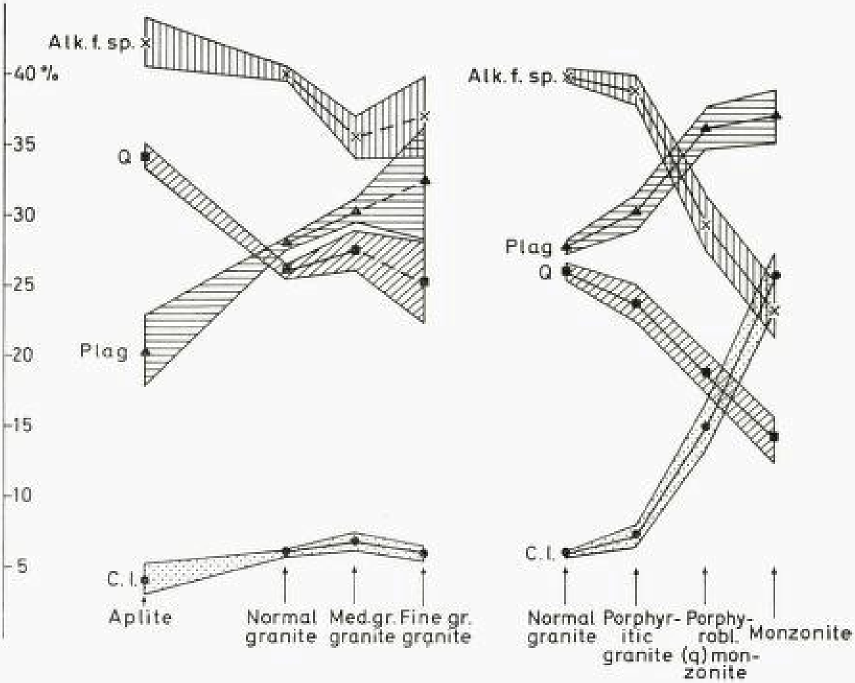

Figure 13. Variation of modal composition and color index of the different rock types within the Grimstad granite. Ranges given correspond to mean value plus and minus standard error of the mean

The modal analyses are, therefore, indicative of a relationship between the mineralogical composition of the medium grained granite and the numerous gneissic and quartzitic rocks of the agmatite zone. In the fine grained granite no such tendency appears, probably because the term "fine grained granite" in the present study includes rocks of different origins.

Another feature clearly demonstrated by Figure 13 is the gradual mineralogical trend from normal granite through medium grained porphyritic and porphyroblastic varieties to monzonite or monzodiorite. Thus the modal analyses indicate that both the medium grained granite and the porphyritic granite are products of assimilation processes. Their texture and composition varies with the location in the granite and may be due to the different composition of the rocks digested, relatively more acid in the western agmatite area, more basic in the middle and eastern sections. This indicates that the assimilation

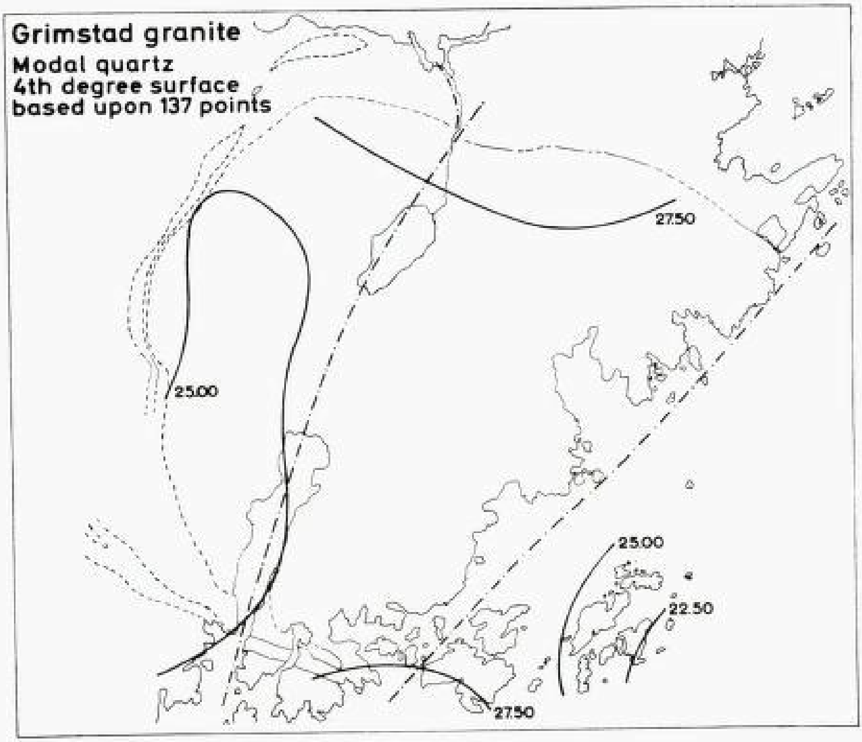

Figure 14 a. Variation of modal quartz in the Grimstad granite. The surface is based upon data from main granite samples plus porphyroblastic (q-) monzonite and monzonite samples of grid points.

becomes stronger towards the center of the granite. In order to examine possible areal modal variations of the normal granite, a trend surface analysis has been performed on the normal grid point samples. The 4th degree surface has been chosen to compare with the equivalent trend surface analysis of the normative variations. Modal quartz and sum femic mineral surfaces are calculated (Figure 14 a and b).

The modal quartz trend surface is saddleshaped, the highest values are situated in the northern and southern end of the middle section, leaving the eastern and western sections as "lows". An opposite, but somewhat more complex trend may be read from the colour index surface. The middle section again constitutes a plateau this time dropping in value in the northern and southern parts, while the western and possibly the eastern flanks are generally higher. The

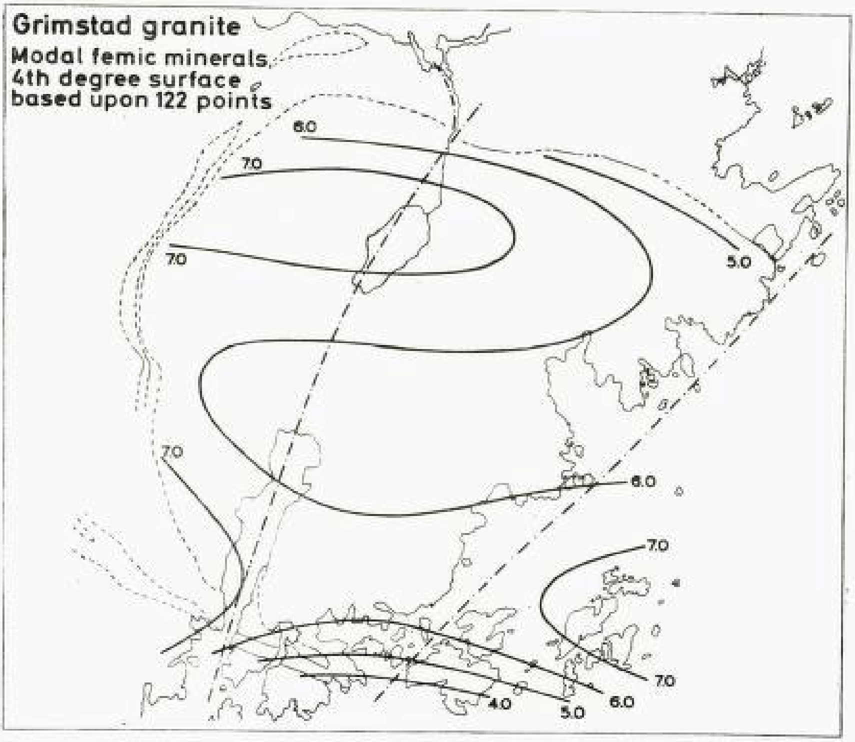

Figure 14 b. Variation of modal femic minerals in the Grimstad granite. The surface is based upon data from main granite grid point samples.

E-W trend in Figure 17 b may also come from the dark types which are most common in the central and coastal parts of the middle section, even if none of the samples of the dark types are included in the analyses.

Mesonorm.

The CIPW norm is well known as a method of calculating the normative minerals of igneous rocks. However, the content of hypersthene in the CIPW norm makes it less useful for biotite granites and for rocks belonging to the mesozone. Barth (1959, 1962) proposed a method of calculating the normative minerals of katazonal and mesozonal rocks, giving the so-called katanorm and mesonorm respectively. The katanorm is practically identical to the CIPW norm, the main difference being that the basis of calculation is cation % rather than weight %.

In the mesonorm biotite and hornblende are calculated rather than hypersthene. Other mesonormative minerals are sphene and spinel, and except for ilmenite and acmite, all other mesonormative minerals are in common with the katanorm.

The mesonormative minerals reflect the actual mineral composition of the different rock types in the Grimstad granite and its host rocks quite satisfactorily.

The variations in the mesonormative composition may be a result of a complicated interplay of many factors. Comparison between mode and norm should therefore not be based upon those minerals that are sensitive to analytical and mesonormative error (Table VI), as Or and Bi. The colour index, on the other hand, is not so much affected by mesonormative error, since erratically low Bi values commonly are compensated for by higher Act content.

Further, a comparison between the modal and mesonormative feldspar is not possible since the modal alkali feldspar contains varying amounts of albite component (see page 72, Table VIII a). In a series of 16 normal Grimstad granite samples the Ab content of the perthite varies between 14 and 24 %.

The quartz and the colour index therefore seem to be the mineralogical variables best suited for a comparison. Table VII which gives the mesonormative mineral variation within one outcrop, shows that these variables have a relatively low deviation.

Figure 15 shows normative quartz content and femic mineral content of the granite. Normative quartz varies only slightly. The major part of the granite is made up of a plateau undulating between 22.5 and 25.0 % with more Q-rich border zones in the north and south and a decrease in the central southeastern part.

The femic mineral map also shows small variations, the largest part of the granite lying between 7 and 8 %. The influence of the assimilated rocks can be seen along the coast where the femic minerals increases, and also in the western part where the 8 % contour touches the granite.

When comparing the modal and normative maps it is seen that although the absolute values of quartz and sum femic minerals differ, the general picture is the same.

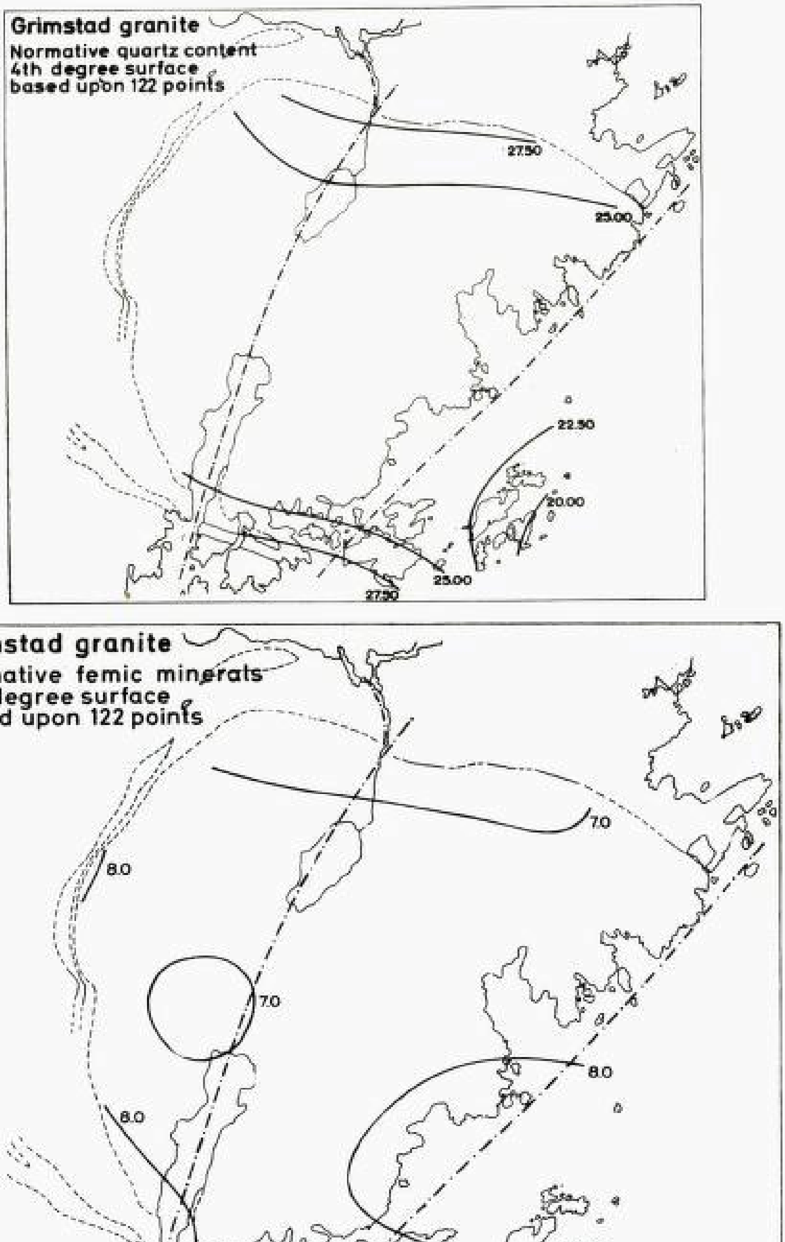

Figure 15. Trend surfaces of normative Quartz and femic minerals based upon main granite grid point samples (122 points).

GEOCHEMISTRY

A description of the sampling system, the sample preparation and the analytical methods is given in the Appendix. The chemical data are available upon request to the authors.

Trend surface analyses.

Computation of trend surfaces has been discussed by several authors. Briefly it can be said that the construction of trend surfaces involves fitting a polynomial surface to a set of data by means of the least squares method. The resulting surface differs from an ordinary isopleth map in giving a more general picture of the variation in an area. Smaller variations will usually not be reflected in the constructed surface. It is the trend in the variation which is important in this connection.

A problem which must be treated separately in each case is the degree of polynomial surface that has to be chosen, in other words how detailed the trend surface should be. A higher degree will give a more detailed surface and fit a particular set of data better, but the surface may then reflect insignificant variations.

For the Grimstad granite 2nd, 3rd, 4th and 5th degree surfaces have been constructed for Fe_2O_3 (total). From this introductory investigation it was decided to use 4th degree surfaces, because this surface seemed to give the best compromise between the different statistics calculated (low significance level, high multiple correlation coefficient).

To investigate the effect of the dark rock types of the Grimstad granite, we have computed two surfaces for each variable. One surface is based on 137 grid point samples, being the total number of grid points, and a second surface is based on 122 grid point samples classified as normal granite where dark types and a few other extreme rock samples have been excluded. These two surfaces will in future be called the 137 surface and the 122 surface respectively.

The construction of a trend surface based on the 15 grid point samples excluded from the 122 surface (to find any possible patterns indicative of their origin), was considered but rejected because the samples were too few and too scattered.

Trend surfaces were computed for Fe_2O_3 (total), CaO, K_2O, SiO_2 and granitization index (see below). The corresponding maps are shown in Figure 16—19, and 21.

The most striking feature about the trend surface maps is the "inverted" differentiation patterns in both the 137 and 122 surfaces. Because of the intrusive character and magmatic appearance of the granite, normal differentiation patterns (i.e. more basic along the margins, more acid in the interior) would be expected, but except for the 137 surface of CaO which has a relatively complicated pattern, all elements show a tendency towards an "inverted" differentiation pattern. That is, high Fe_2O_3 and CaO in the center decreasing towards the margins, and low K_2O and SiO_2 in the center increasing towards the margins. This tendency is most pronounced in the 137 surface due to the influence of large areas of dark rocks along the coast.

More surprising, however, is the fact that the same tendency dominates the 122 surfaces where the dark rocks have been excluded. The area of chemical minimum (or maximum) is moved somewhat in the NE direction, and the location of the contour lines on the surface may be somewhat different in detail, but the general picture is the same.

This leads us to ask if the granite has ever differentiated in the classical way, leading to basic edges and a more acid interior, a hypothesis which seems not to be confirmed by these data. The most probable explanation seems to be that the contamination by basic country rocks has influenced the chemical composition of the normal granite. Whatever the chemical distribution in the granite massif has been, it now seems to be obscured by the chemical changes induced by this contamination.

Similar inverted differentiation trends have been found in other granites (Ragland, Billings and Adams, 1968; Cook and Rogers, 1968).

The western part of the granite shows, in some cases, smaller chemical variations than does the middle section from Birketveit to Rønnes. This is particularly well illustrated by the K_2O surfaces where the middle section includes almost the whole range of variation with an increase in the slope of the surface towards the margins. The steep slope in the southern part of the granite obviously reflects the presence of aplites in this area. In the western section the surface flattens out and contains only a fraction of the total variation. In other words the western section seems to be more homogeneous and

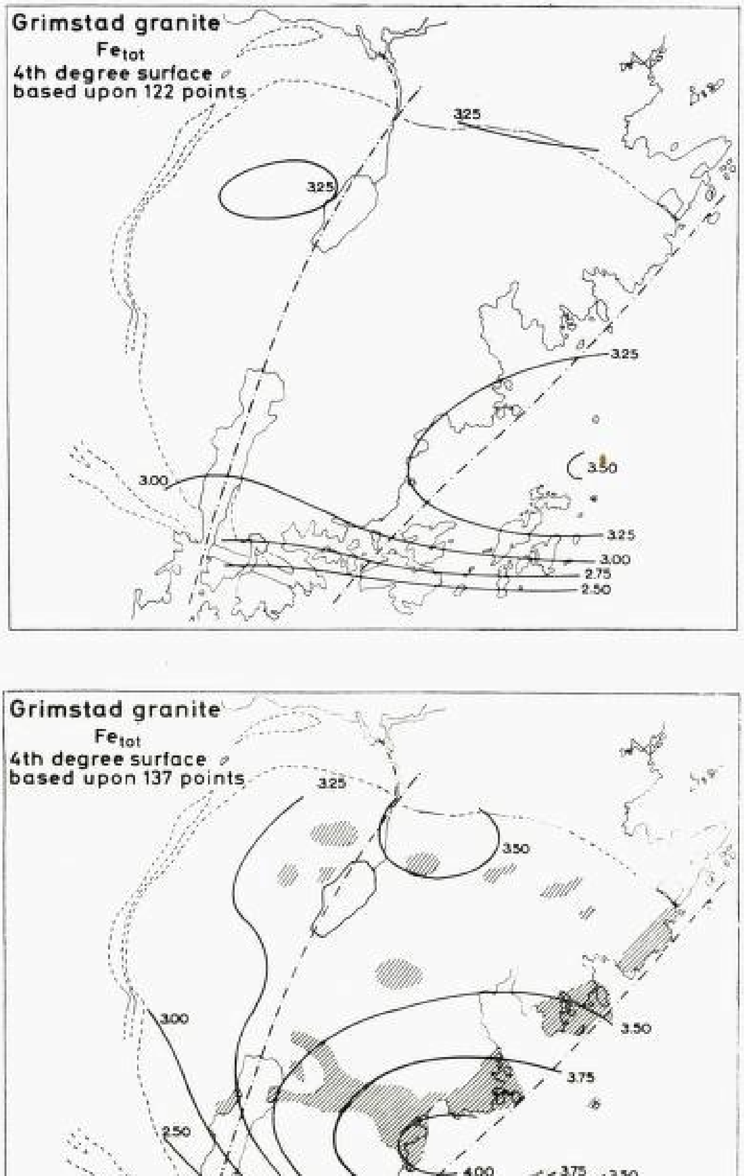

Figure 16. Trend surfaces of total Fe as Fe_2O_3 based upon main granite grid point samples (122 points) and total number of grid point samples (137 points).

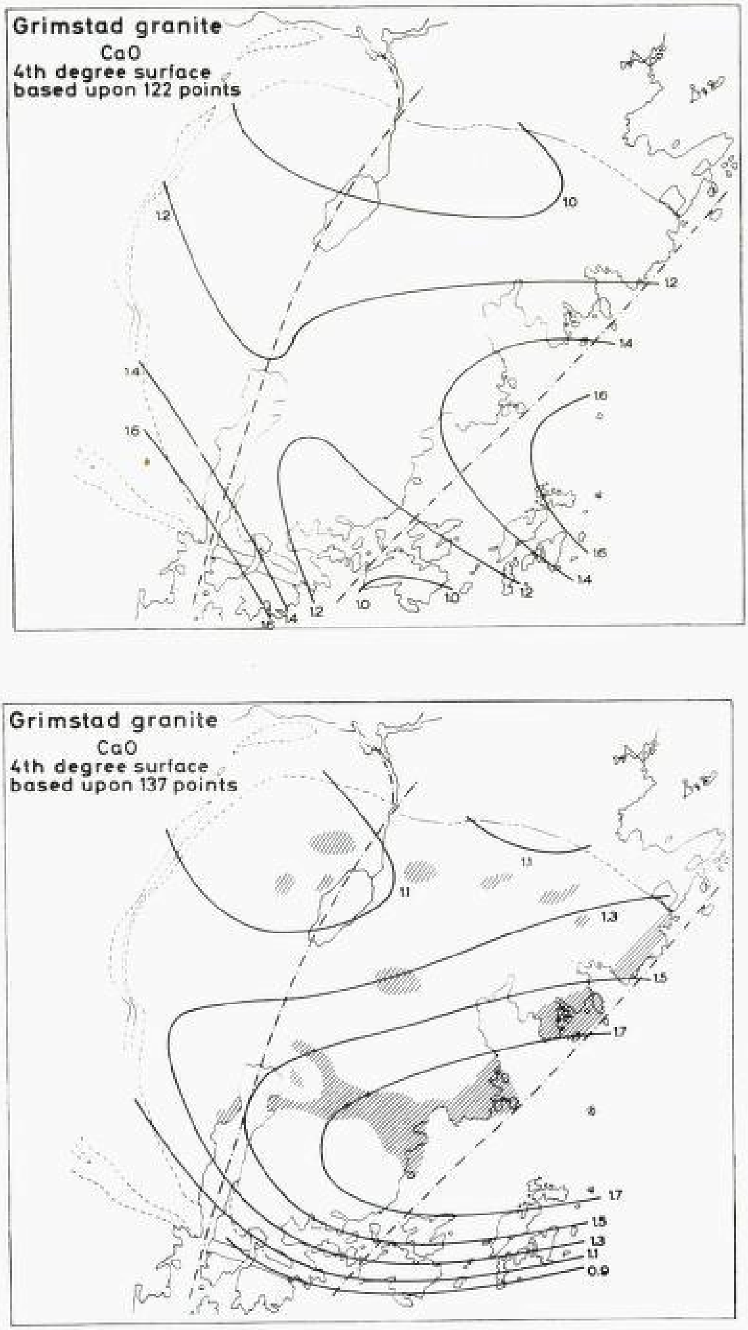

Figure 17. Trend surfaces of CaO based upon main granite grid point samples (122 points) and total number of grid point samples (137 points).

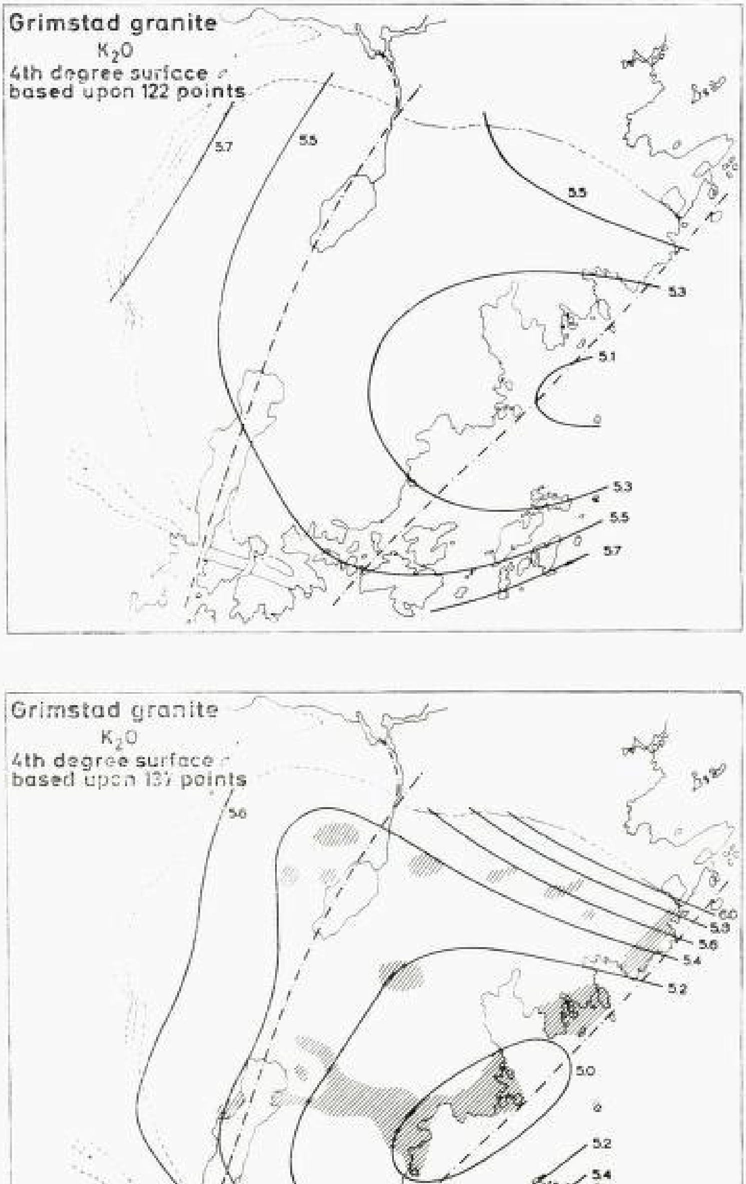

Figure 18. Trend surfaces of K_2O based upon main granite grid point samples (122 points) and total number of grid point samples (137 points).

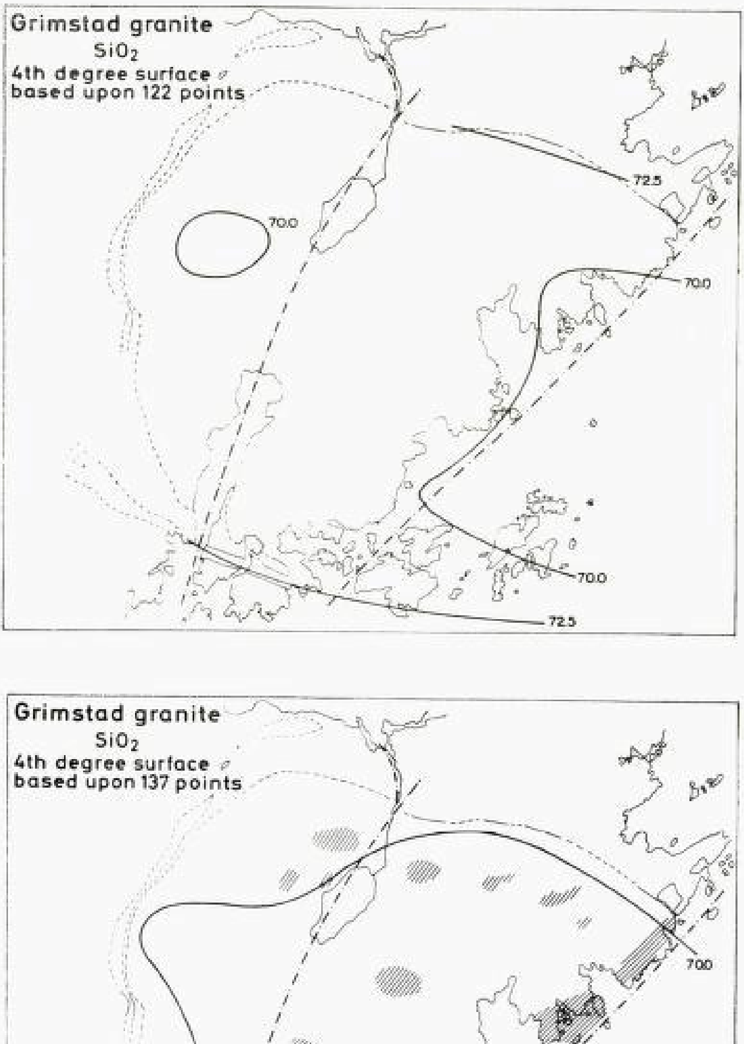

Figure 19. Trend surfaces of SiO_2 based upon main granite grid point samples (122 points) and total number of grid point samples (137 points).

also richer in K_2O than the middle section. A t-test also shows that the two sections are different at a 95 % confidence level.

Generally, the western part shows not only less variation than the middle section, the contour patterns in this part are also considerably more complicated, possibly indicating a slightly different petrogenetic history for the two parts of the granite.

Other evidence supporting this theory is found in the Sr content of the plagioclases. Most of the analyzed plagioclases from the middle section are richer in Sr than the plagioclases from the western and eastern section.

Another indication is the difference in border relations. The agmatite zone of the western section is totally different from the sharp borders of the middle section.

In the SiO_2 surfaces the variations are small, but a tendency towards more acid margins can be seen particularly in the 137 surface.

Generally the shape of the surfaces does not change very much when the extreme rock types are removed. In the case of CaO, however, the trend in the SW part of the granite is reversed when going from the 137 to the 122 surface. In the 122 surface the central section shows the usual high Ca center with a decrease towards the margins, while the SW part shows an incrase in CaO from N to S. It is difficult to decide, however, whether this is a geologically significant trend or mainly a result of a single, outstanding value. Since the contours in this area are based on relatively few samples, the trend surface is likely to be more strongly influenced by possible outliers.

Element correlations.

The correlation matrix of the complete set of 137 analyses is given in the table of Appendix. An attempt was made to test the significance of the correlation coefficients by the Chayes-Kruskal method (Chayes & Kruskal, 1966), but zero values outside the permitted range +1 to —1 were obtained for the present material for several element pairs. Such impossible values may occur if there are unconsidered strong correlations between the data and some parameter not included in the data, and for the Grimstad granite there is a correlation between geographic coordinate and chemical composition that may contribute to "impossible" zero values.

The Mosimann test (Mosimann, 1962) gives very low zero values for several igneous rock series, and this is true for the Grimstad granite as well. Therefore the Mosimann test seems to be insufficient to point out insignificant correlations generated by the closure of data material from igneous rocks.

Significant negative correlation is found between SiO_2 and all the other elements but NaO_2, and for the element pairs TiO_2/K_2O, Fe_2O_3/K_2O, and K_2O/P_2O_5. Positive correlation is found for the component pairs TiO_2/CaO, TiO_2/P_2O_5, Al_2O_3/Na_2O, Fe_2O_3/MgO, Fe_2O_3/CaO, Fe_2O_3/P_2O_5, MgO/CaO, MgO/P_2O_5, and CaO/P_2O_5.

The frequency distribution of SiO_2 corresponds to a near log-normal distribution with negative skewness, most frequent values fall in the range 69—71 % SiO_2, and there are two insignificant peaks in the low SiO_2 range which are due to dark rock inclusions being overrepresented relative to their geographic extension.

Granitization of included rocks.

Granitization is commonly examplified by growth of alkali feldspar porphyroblasts, often across sharp borders between granite and country rock. However, granitization may be manifested in different ways, taking into account the feldspathization alone does not seem sufficient in all cases.

In included amphibolite fragments in the SW part of the granite the first evidence of granitization is transformation of hornblende into biotite, then comes the growth of alkali feldspar, first as small crystals in the groundmass, later as porphyroblasts. This also seems to be the case in the dark and porphyroblastic types of the Grimstad granite.

The granitization of less basic rocks may lead to feldspathization at an earlier stage, simply because these rocks contain smaller amounts of dark minerals to be altered. The growth of alkali feldspar porphyroblasts thus seems to depend more on the original chemical composition of the inclusions and less on the total influx of granitizing agents.

To trace the granitization processes in the Grimstad granite we, therefore, wanted to make use of variables other than the content of alkali feldspar, and a triangular diagram Ca — Na+K — Fe^{II}+ Mg was constructed (Figure 20). This diagram gave an unambiguous trend

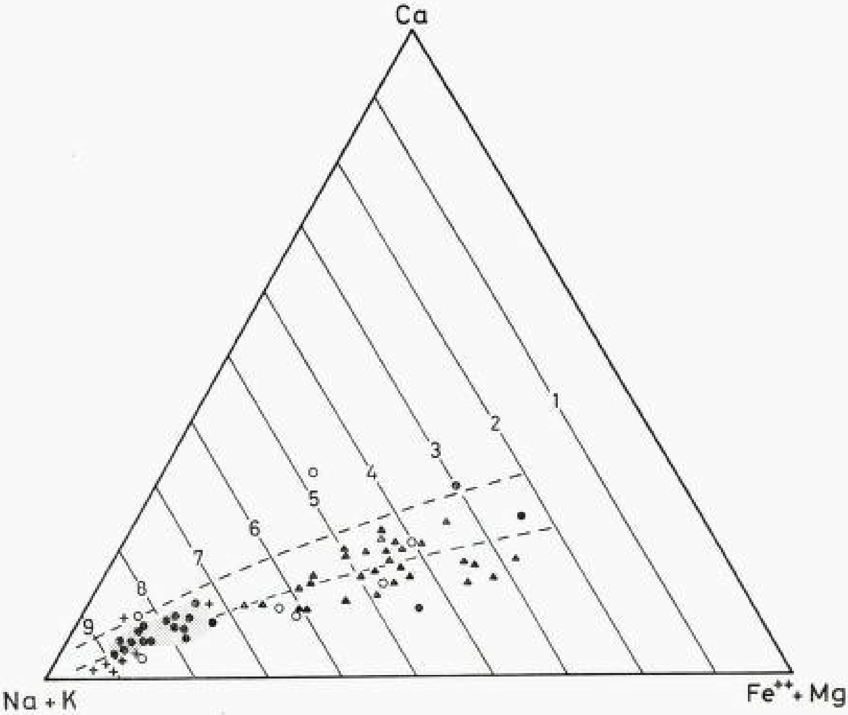

Figure 20. Plots of different rock types in the Na+K, Ca, Fe^{+2} + Mg diagram. Open circles = gneisses of the immediate surroundings and the agmatite zone, closed circles = amphibolites, triangles = porphyroblastic (q-) monzonites and monzonites. The normal granite plots fall inside the shaded area.

from non-granitized amphibolites through partly granitized amphibolite inclusions, monzonites and porphyroblastic (q)-monzonites to the normal granites with the aplites as the extreme end. The diagram may be divided into zones defining the granitization index Gr. I. (Thoresen, 1966), and each sample will then be assigned a Gr. I.-value. It should be noted that this diagram may also be used to illustrate a magmatic differentiation trend. In the case of the Grimstad granite the diagram combines these two possibilities, showing increasing granitization in the lower and medium Gr.I.-range and late stage differentiation in the high Gr.I.-range. For simplicity the index will, however, be referred to as "granitization index". Using the Gr.I.-value as variable, a trend surface was constructed showing the degree of granitization over the granite (Figure 21).

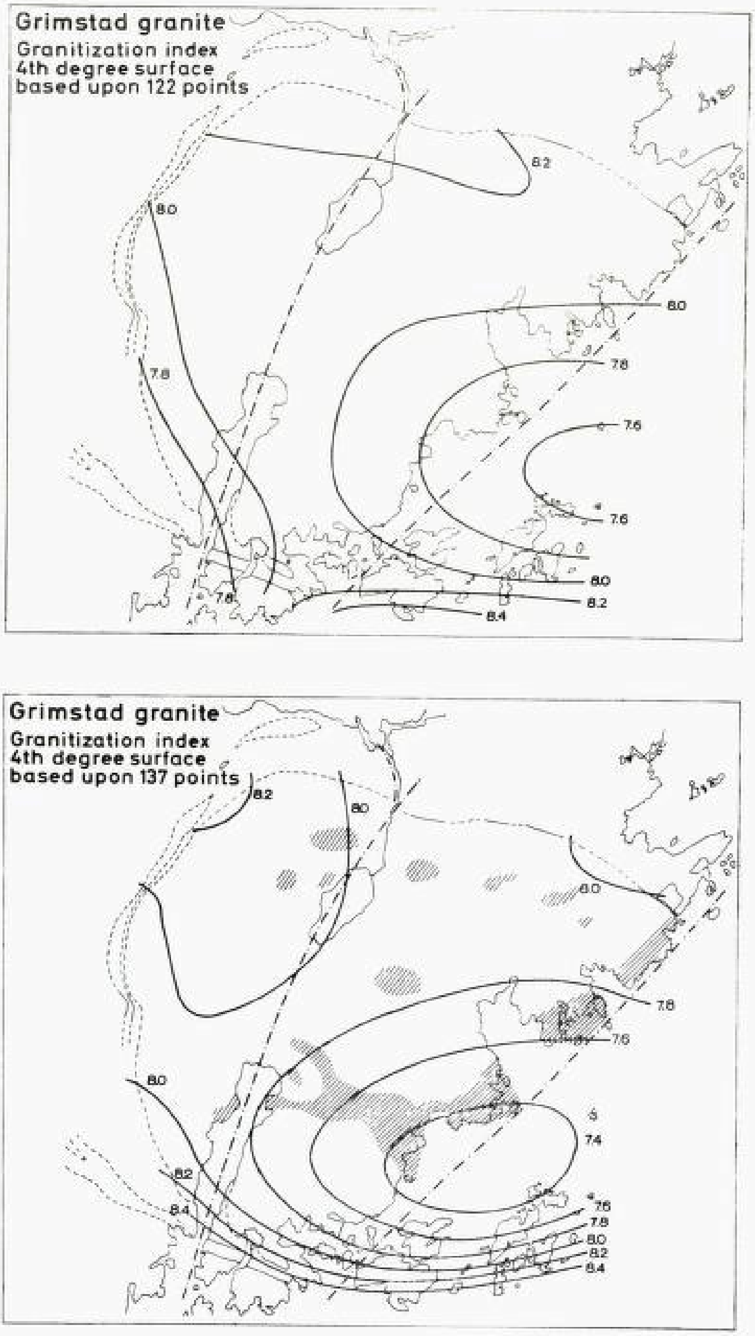

Figure 21. Trend surfaces of granitization index based upon main granite grid point samples (122 points) and total number of grid point samples (137 points).

Due to the presence of dark and porphyroblastic types the granitization surface is low at the center of the granite and the pattern is concentric. This pattern coincides particularly well with the Ca surface which may be used as a rough indicator of the granitization.

The concentric pattern may, in our opinion, be interpreted as the result of an ascending granite body, possibly with a more acid and chemically more active cap which facilitates the assimilation of the country rocks.

The central part consists of more thoroughly granitized basic rocks, either brought up from the gneissose substratum or included from the roof. These rocks have been able to alter the chemical composition of the surrounding granite to a certain extent, while the inclusions along the margins are sharp edged and relatively unaltered, indicating that the exchange of material between the granite and the inclusions has been too small to change the composition of the granite on a larger scale.

We are thus inclined to think that the concentric pattern of the granitization surface is an important and characteristic feature of the Grimstad granite and not the result of an admixture of a random set of foreign rock types in our material.

Chemical analysis of the feldspars.

To obtain more detailed information about the relationships between the different subtypes of the Grimstad granite, a series of 22 samples lying on two profiles (Fig. 22) were subjected to mineral separation, and the alkali feldspar and plagioclase were analyzed for Na, K, Ca, Rb and Sr.

The quantitative distribution of different subtypes in these profiles corresponds roughly to the distribution in the granite. The classification and the chemical analyses of the samples are given in Table VIII a and b.

Major elements.

The alkali feldspars are normal microcline perthites with a composition varying from 73Or/25Ab in the monzonitic types to 90Or/9,5Ab in the aplite. The variation is well outside the limits of analyti-

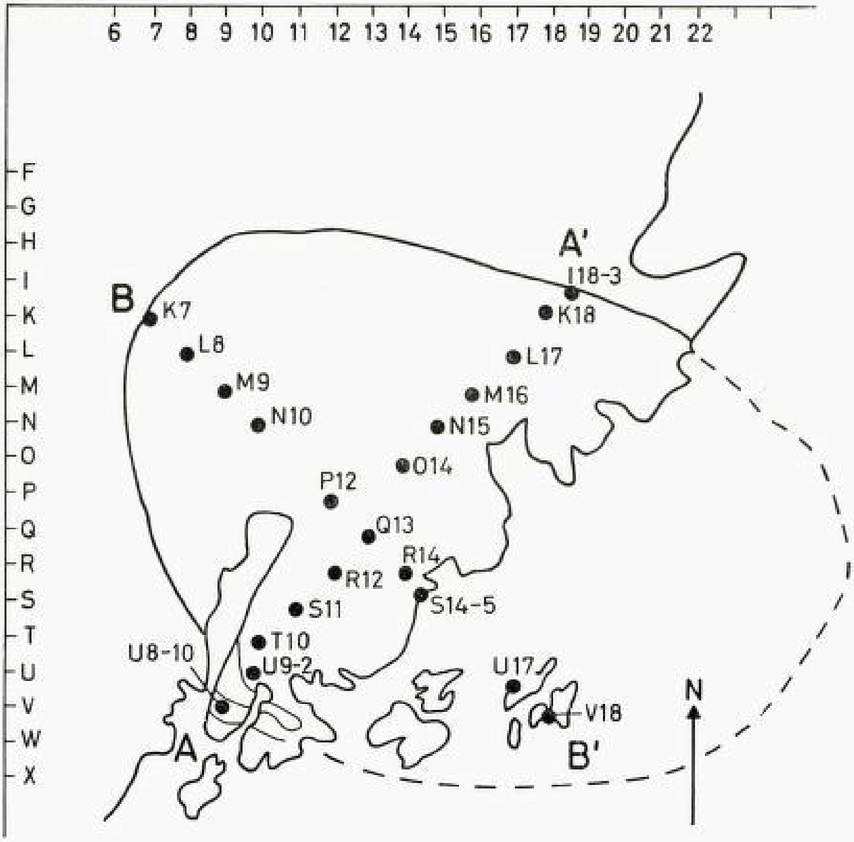

Figure 22. Sample stations of specimens for chemical investigations of feldspars.

cal error and reflects variations in the bulk composition of the different granite types.

The plagioclases are albite-oligoclases with a slight tendency towards higher An content in the monzonitic types and lower in the aplitic and acid types (Q 13). As mentioned in the Petrography chapter, the two types of plagioclase in the normal granite differ in An content, and the chemical analyses probably represent an average of the two types.

The unusually high K_2O values of the plagioclases may be explained by the strong sericitization.

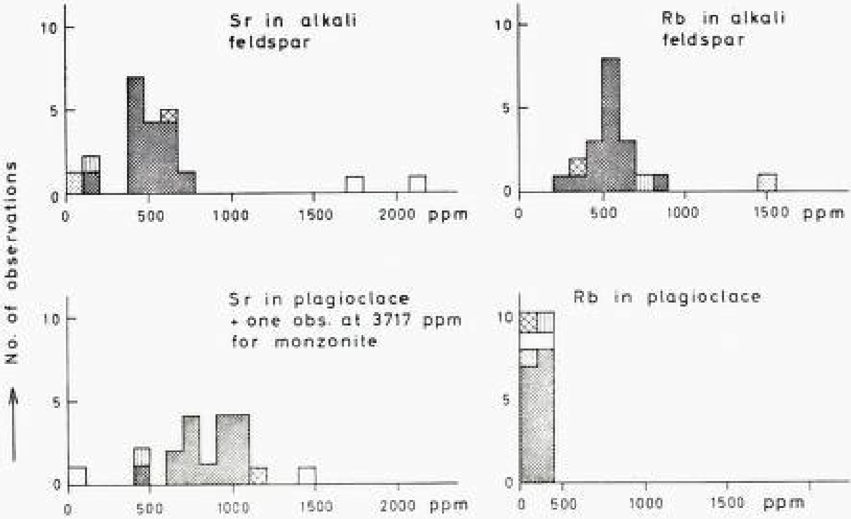

Figure 23. Frequency distribution of Sr and Rb in feldspars of the Grimstad granite. Grey: normal granite, white: monzonites, stippled: aplite, crosshatched: medium grained, lined: fine grained.

Rubidium and strontium

Alkali feldspars.

In the normal granite, Rb in alkali feldspars varies between 295 and 826 ppm with a mean value of 543 ppm (Figure 23). The values for the fine grained and medium grained granite feldspars also fall within this interval. The aplite feldspar is particularly rich in Rb and should be interpreted as a late differentiate if a magmatic hypothesis is to be followed.

The monzonitic types R 12 and S 14-5 are very low in Rb. While the average Rb/Sr ratio in the normal granite alkali feldspars is close to unity, the same ratio in the monzonites is 4/100 and 1/10 respectively. If these types are interpreted as assimilated inclusions of basic country rocks, their low Rb content may be inherited from the original rocks, either amphibolites or arendalites.

The Rb content of the porphyroblastic monzonite feldspar (S 14-5) lies between R 12 and the normal granite, which is consistent with the idea that the porphyroblastic types are more thoroughly granitized monzonites.

Sr in the normal granite alkali feldspars varies between 165 and 756 ppm with a mean value of 524 ppm (Figure 24). The alkali

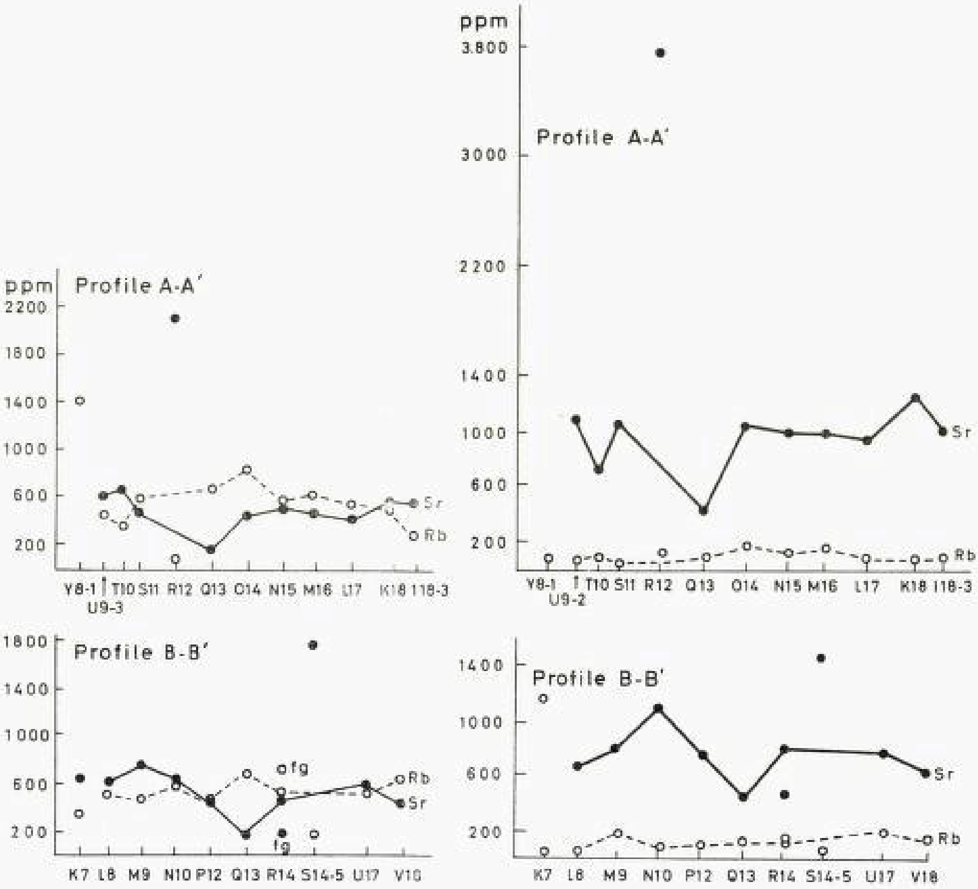

Figure 24. Left: Values of Sr and Rb in alkali feldspar. Fully drawn and dotted lines connect points from main granite feldspar samples. Right: Values of Sr and Rb in plagioclase. Fully drawn and dotted lines connect points from main granite feldspar samples.

feldspars in the monzonites have three to four times as much Sr as the normal granite. Again we observe the same relationship between the monzonite, the porphyroblastic type and the normal granite.

The aplite feldspar is considerably lower in Sr than the normal granite. This is also the case for the fine grained granite (R 14 fg), possibly indicating a late stage genesis. Q 13 also deviates from the normal granite on account of its low Sr content. Q 13 is, however, taken from an area rich in inclusions and may represent a granitized quartzite or quartz-rich gneiss, macroscopically similar to the normal granite.

Plagioclases.

The Rb content of the plagioclases is low compared to that of the alkali feldspars (Figure 25). The spread of values is also small, and it is not possible to distinguish different subtypes on the basis of Rb content. This is in accordance with the results of earlier works which have shown that the Rb content is low and rather uniform in plagioclases of different composition. It is suggested that this indicates only limited substitution (Heier, 1962). The difference in ionic radii between Rb and Ca/Na may prohibit the entry of Rb in lattice positions.

Compared with Heier's data the Grimstad granite plagioclases are relatively high in Rb. This is probably due to the sericite content of the plagioclases, Rb entering the muscovite lattice more easily.

The frequency distribution of Sr in the normal granite plagioclases shows two peaks, one between 700 and 800 ppm, the other one around 1000 ppm (Figure 25). This may be correlated with the An content of the plagioclases. There is a tendency towards lower Sr content in the more albitic plagioclases. The number of samples is small, however, and it is not possible to tell whether this two-peak distribution is representative for the normal granite or not. But it is worth mentioning that the plagioclases with high Sr content are found mainly in the middle section from Rønnes to Birketveit, while the Sr poor plagioclases are found mainly in the western and marginal south eastern part of the granite.

As seen from Table VIII b the positive correlation between Sr content and the An content of the plagioclases also holds for the other subtypes in the granite.

Summary.

The variation in the Rb and Sr content of the feldspars is large, both with respect to the absolute content of Rb and Sr and relative to the major element content. There seems to be no definite relationship between the trace element content and the distance from the granite border, even if only the normal granite is considered (Figure

24 a and b). In the alkali feldspars there is a tendency towards higher Rb content in the central part of the granite in the NS profile but this is not found in the EW profile.

The different subtypes are easily distinguished on the basis of their Rb-Sr content, except for Rb in the plagioclases. This also holds true for the Rb-Sr content of the bulk rock as shown by Table IX below.

K/Rb ratios in the feldspars and bulk rock.

The K/Rb ratio is commonly used as a geochemical indicator of magmatic differentiation, a decreasing ratio meaning increasing degree of differentiation. Taylor (1965) gives an average K/Rb value of 230 in rocks and minerals, the normal spread of values being from 150 to 300. Lower values are characteristic of late stage granites and pegmatite feldspars. Higher values are less common, but have been found in alkali feldspars from charnockites and syenites (Taylor and Heier, 1958; and Upton, 1960) and in oceanic tholeiites (Shaw, 1968).

Alkali feldspars

In the normal granite alkali feldspars K/Rb ratios vary between 136 and 342, a notable variation within one single granite body. The areal distribution gives somewhat higher values towards the granite border in the NS profile, but this tendency is not found in the EW profile.

The ratio for the fine grained granite feldspar lies in the same interval as those of the normal granite, while the low value of the aplite feldspar again suggests late stage genesis. The monzonitic types with their extremely high values show a marked deviation from the main trend, this excludes them from being possible early differentiates of the granite magma. Taking the relative amounts of the monzonitic rocks to normal granite into consideration, it seems unlikely that crystalline differentiation is the mechanism responsible for the extreme reduction of the K/Rb ratio from the monzonites to the normal granite.

As pointed out by Taylor (1965) a magma starting to crystallize with a K/Rb ratio within normal limits, will yield rocks with decreasing K/Rb ratios. There seems to be no way in which a differentiating magma can increase its K/Rb ratio except by assimilation of rocks with higher K/Rb ratios.

Bulk rock.

In the country rock complex there are at least two groups of rocks which should be able to supply material for an assimilation of that type, the amphibolites and the charnockitic hypersthene gneisses called arendalites.

The few data that exist on K/Rb ratios in amphiboles and amphibolites seem to point towards values well above the average. Griffin, Murthy and Phinney (1967) give values between 170 and 1750 from a series of amphiboles and their host rocks from Minnesota, and values up to 5000 are given by Hart and Aldrich (1966) in a survey on amphibole analyses. K/Rb analyses of 7 amphibolites from the country rock complex north of the Grimstad granite also confirm this trend, they lie between 355 and 1666.

Assimilation of amphibolites with a corresponding redistribution of K and Rb would therefore be able to produce rocks similar to the Grimstad monzonites. The content of hornblende, (usually altered) and the late formation of alkali feldspar in the monzonites also points towards amphibolites as a possible source material for the monzonitic types.

The arendalites carry mesoperthitic feldspars with anomalous K/Rb ratios up to 1200 (Heier and Taylor, 1958). These rocks are found less than 1 km from the northern granite border where they grade into amphibolites and banded gneisses.

Relict hypersthene is also found in a few monzonitic samples, indicating that at least some of them may be interpreted as inclusions of arendalites. The sparseness of hypersthene may be explained by the strong granitization of most of the included rocks, leading to the alteration of hypersthene into amphibole and biotite at an early stage.

The discussion so far has mainly been concerned with the K/Rb selectivity of the alkali feldspar. Conclusions are based on the assumption that anomalous K/Rb ratios in the alkali feldspars imply anomalous ratios in the whole rock. This may be the case, but it must also be borne in mind that Rb tends to concentrate in biotites when the K/Rb ratio in the bulk rock is normal, suggestion that certain conditions of formation cause biotite to show marked Rb selectivity. In a biotite rich rock this could be sufficient to alter appreciably the K/Rb ratios of the feldspars which would then be reflecting "availability" at the time of feldspar formation and not the ratio of K/Rb in the whole rock.

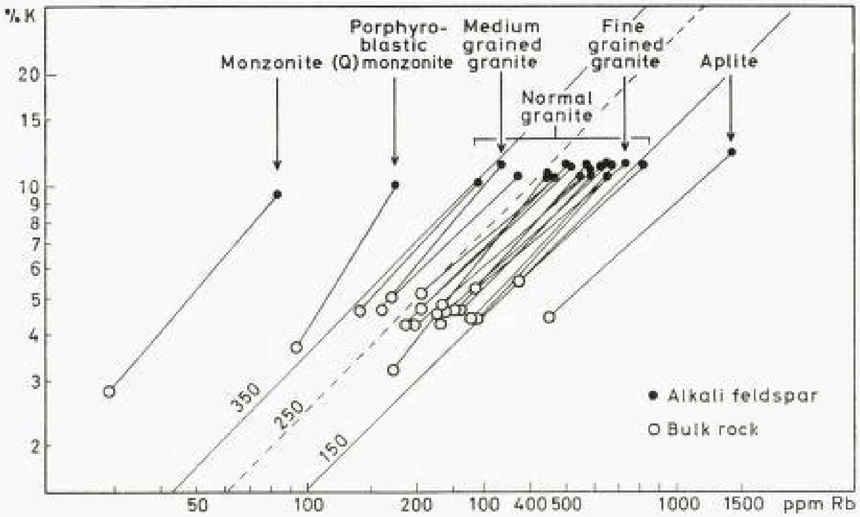

Figure 25. Potassium and Rubidium in alkali feldspars and bulk rock samples.

To investigate this problem, the profile samples plus a series of monzonites, dark amphibolitic inclusions in the granite border zone, and surrounding amphibolites and gneisses were analyzed on bulk K/Rb (Table X). The location of these samples are given in Fig. 22.

Fig. 25 shows the K/Rb ratio of the bulk rock compared with the K/Rb ratios of the alkali feldspar in the profile samples. It is clear that anomalous ratios in the feldspars correlate positively with anomalous bulk ratios although the latter are not equally extreme. The anomalous K/Rb ratios of the monzonites must therefore be considered real and not the result of selective entry of Rb into biotite.

Fig. 26 shows the bulk rock K/Rb ratios of some of the surrounding amphibolites and gneisses together with the dark inclusions, monzonitic types and the normal, medium grained, fine grained and aplitic granite. The relationship between the monzonites, the inclusions and the amphibolites seems obvious and supports the theory of amphibolites as source material for the monzonitic varieties.

The gneisses, on the other hand, seems to have too low K/Rb ratios to produce monzonites, but it is not unlikely that some of the fine grained and medium grained granites, and even the normal granites, may have developed from gneissic inclusions.

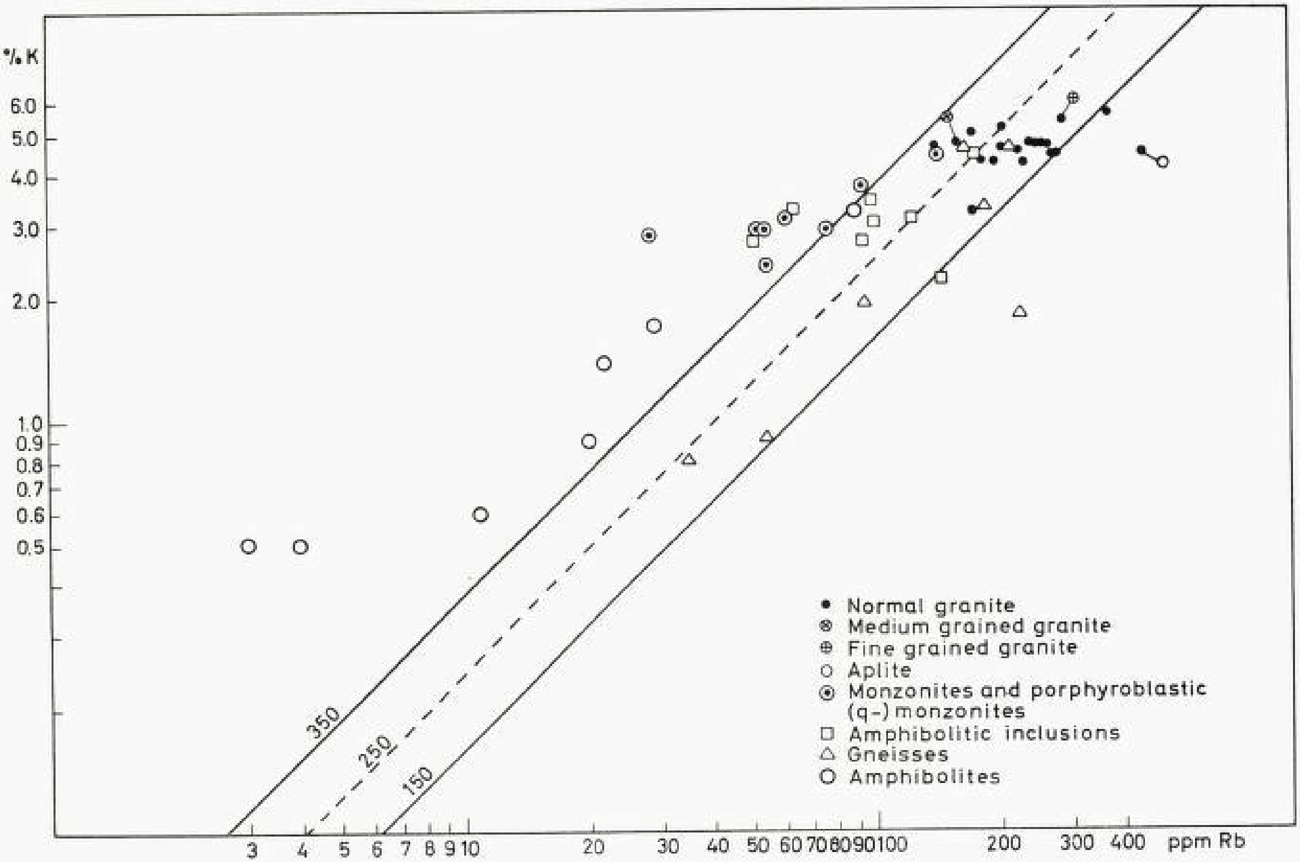

Figure 26. Potassium and Rubidium in samples from the Grimstad granite and its immediate surroundings.

CRYSTALLOGRAPHY OF ALKALI FELDSPARS

Obliquity — delta values

Alkali feldspars tend to grow in the monoclinic or near monoclinic state at any temperature (exemplified by sanidine, monoclinic adularia and monoclinic authigenic K-feldspar). The Al/Si ordered state is often reached through an intermediate R△ state (RD state of Christie, 1962) that gives characteristic blurred X-ray reflections (Laves, 1950; Goldsmith and Laves, 1954). The R△ state is, thus, indicative of non-equilibrium of the monoclinic-triclinic transition of K-rich alkali feldspars.

The obliquity of 531 alkali feldspar samples from the Grimstad granite were determined from X-ray powder films, made in a Nonius-Guinier quadruple focussing powder camera. The results are displayed in Figure 27.

All alkali feldspars samples from the normal granite gave high delta values, and this is also true for the examined aplite specimens and all specimens in the group of medium and fine grained granites with one exception (H 14-1). The mean value and estimated standard deviation of the obliquity of the main granite alkali feldspars are 0.95 and 0.02 respectively.

Special attention was given to the feldspars of the dark inclusions since we believed that they could supply information about the genesis of the inclusions. They regularly give R△ X-ray powder patterns (Table III), and we think this is a result of relatively rapid growth and insufficient time for complete inversion into the triclinic state. This can be studied at the coast East of Fevik, particularly at the locality O19. R△ alkali feldspars have also been found in normal granite samples.

The distribution of R△ alkali feldspars falls into two cathegories: In the middle section they are found in the dark varieties, but in the western section the distribution is scattered and bears no obvious relation to bulk chemical composition of the rocks. We think that this may be explained from the hypothesis that the R△ feldspars of the western section formed in inclusions of granitic gneiss or other country rocks of acid composition which were more easily transformed into normal granite by assimilation than the basic rocks of the middle section.

Nilssen and Smithson (1965) reported that low △ and R△ alkali

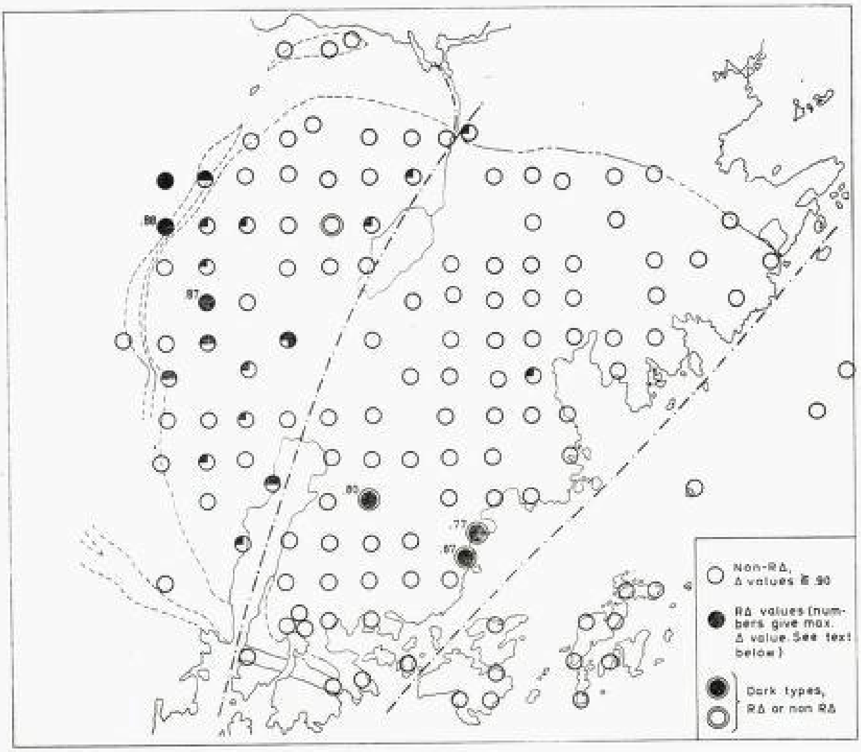

Figure 27. Obliquities (Delta values) of alkali feldspars. Four specimens were collected from each sample station, thus each circle represents four observations.

feldspars are associated with the dark varieties of the Herefoss granite. This is true for the middle section of the Grimstad granite, but not for the western section. The correlation between bulk chemical composition and delta value of alkali feldspar advocated by Nilssen and Smithson must be of secondary nature; the occurrence of the R△ pattern of alkali feldspars is indicative of incomplete transition from the monoclinic to the triclinic state and in the Grimstad granite such alkali feldspars are found in incompletely assimilated country rocks.

In the middle section of the Grimstad granite the incompletely assimilated country rocks with newly grown alkali feldspars are mostly basic, and hence there is a correlation between distribution of low △ and R△ alkali feldspars, and dark rock types. In the western section, however, the assimilated country rocks seem to be derived from more acid rocks, like granitic gneisses, and the distribution of low △ and R△ alkali feldspars has no correlation with distribution of dark rock types in this area.

Single crystal work

A series of 40 exposures was made with a STOE Buerger Precession Camera in an attempt to shed some light upon the genesis of the

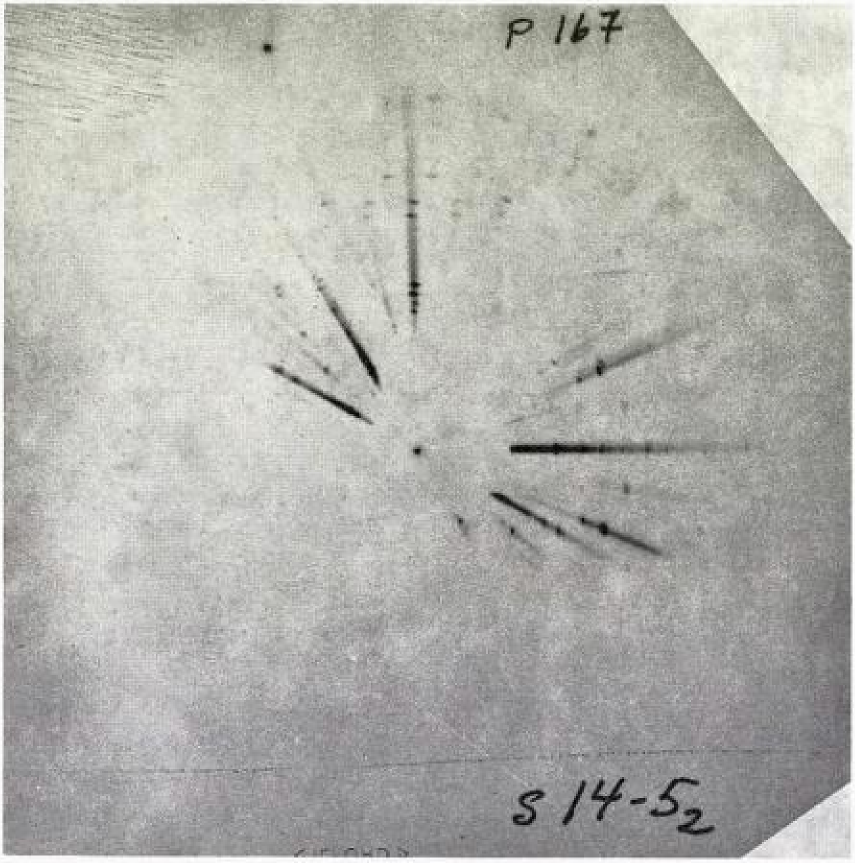

Figure 28. Oscillation precession exposure with c *as precession axis of an orthoclase microperthite from the sample station S 14-5, unfiltered radiation. The* b^* *axes run horizontally, the* a^* *axes vertically. The direction of the* a^* *axis of the K-rich phase (lower reflections of each reflection pair along the* a *axis) does not coincide with that of the* a^* *axis of the Na-rich phase. This feature is referred to as skewness in the text.*

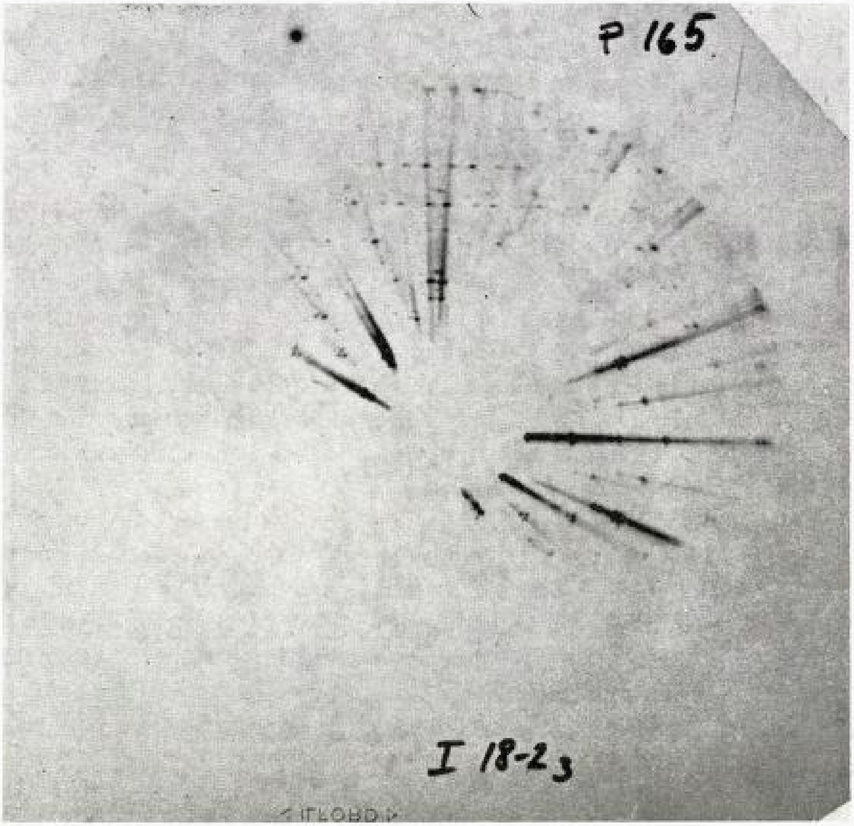

Figure 29. Skewed perthite of Type I of Laves and Soldatos (1962 c). Specimen taken from the red core of a porphyroblast in a dark rock inclusion at the locality K 18-1. Precession axis c, b^* axes run horizontally, a^* axes vertically. The splitting up of the (h00) reflections due to albite law twinning is obvious, and the a^* axis of the exsolved albite is not situated exactly midway between the a^* axes of the K-rich phase. The reason for the occurrence of such skewed perthites is not known.

alkali feldspars. The number of exposures is too small to allow any definite conclusions, but the following general observations may be important:

The majority of alkali feldspar is composed of a triclinic K-rich host and a triclinic Na-rich guest. In many of the samples the a^* axis of the host and that of the guest do not coincide. It has not been possible to relate the differences in a^* directions to special genetic features.

We have applied the notation introduced by Laves and Soldatos (1962 c) for the perthites, adding s (for skewness) for those samples where the a* axes of host and guest do not coincide. The skewness may be a remnant of the monoclinic past of the host, since we have found one orthoclase perthite (monoclinic host, triclinic guest) that exhibits skewness as well (Figure 28).

A slight "Verzerrung" (deviation from exact perpendicularity of the pericline law twin axis to the albite law twin plane) as observed by Laves and Soldatos (1962 b) in pegmatite feldspars, is possibly present in some samples from the bleached granite contact at Birketveit.

In some cases the reflections along the a* axis of the Na-rich phase are elongated in the direction of the b* axis. This may indicate that most of the guest was precipitated in a monoclinic host and that the inversion into triclinic symmetry was initiated before the exsolution of the Na-rich phase was completed.

One alkali feldspar crystal of an inclusion has been studied in some more detail. It occurs as a 1 cm long porphyroblast in a dark inclusion at the locality I 18-2. The red core is a perthite of Type I s (Figure 29), whereas the grey marginal zone consists of perthite Type II s. In this case the margin may have converted into triclinic symmetry before exsolution more easily than the red core because of its contact with the matrix of the inclusion which must have had a relatively high water activity.

The above observations seem to support the hypothesis that the following sequence of events took place:

1. At an early state of the genesis of the Grimstad granite all alkali feldspars of the magma were monoclinic.
2. Exsolution of an Na-rich guest took place mainly before the conversion of the host into triclinic symmetry, this leading to formation of perthites of Type I or I s.

The alkali feldspar porphyroblasts of the inclusions are different. They can be triclinic, but monoclinic symmetry has been observed in a number of samples (Figure 28), inferring that they formed at a late stage in the genesis of the granite. Exsolution may have taken place even after the inversion into triclinic symmetry, thus leading to formation of perthites intermediate between the Types I and II, or I s and II s respectively.

DISCUSSION AND CONCLUSIONS

From its sharp and partly discordant borders and the many angular inclusions, the intrusive character of the Grimstad granite seems indisputable. The existence of the agmatite zone and the large rotated amphibolite blocks in the country rock to the north of the granite, adds to the impression of a forceful intrusion of the Grimstad granite.

A prominent Bouguer anomaly is produced by the granite and is of a type which indicates that the massif extends downwards to a considerable depth, and is in this respect different from several other Norwegian Precambrian granites, such as the Herefoss granite, and especially the Flå and the Iddefjord granite (Smithson, 1963 b and pers. comm.). The source of the granite magma must, therefore, be sought at deeper levels in the crust.

Rocks in the granulite facies may supply material for the formation of granite magma (see for example a review by Mehnert, 1959), and granulite facies rocks are common to the north of the Grimstad granite. If gneisses supply a granitic melt as a result of partial melting, the residue would be a cordierite-garnet rock. Even though the cordierite-garnet rocks common in some parts of the Bamble area have been interpreted as recrystallized magnesia rich sediments (Bugge, 1943), one cannot exclude the possibility that they are such residues. We do not by this suggest that the cordierite-garnet rocks of the Bamble area have supplied material for the Grimstad granite but we think that similar rocks might be found near or at the basement of the granite stock.

Many of the characteristic textural features of the granitic and monzonitic varieties of the Grimstad granite are similar to rapakivi textures, perhaps especially to the wiborgite rapakivi described by Wahl (1925). The common texture of large subhedral microcline perthites mantled with albite-oligoclase, and accompanied by euhedral phenocrysts of alkali feldspar, all of which are situated in a matrix of two generations of feldspar together with quartz and biotite, is consistent with the wiborgite rapakivi.

Furthermore, discordant contacts with the country rocks, agmatitic border relations, only sporadic signs of foliation or flow structure, and lack of conspicuous chilling effects at the borders are properties common to both the Grimstad granite and the rapakivi plutons. (See for example Volborth (1962) and references cited). And, again like most rapakivi granites, the Grimstad granite has a predominance of associated aplitic dikes rather than pegmatites.

Since we have stressed the numerous "rapakivi features" of the Grimstad granite, it is only correct to point out that differences do exist: In the Grimstad granite both mantled plagioclases and alkali feldspars are found, even in the same hand specimen (Figure 11) whereas in rapakivi granites only alkali feldspars are mantled. As stressed by fennoscandian authors, the mantled feldspars in a typical wiborgite rapakivi are ovoid orthoclases, not subhedral microclines. The crystallization sequence of rapakivi granites — orthoclase and quartz crystallizing before biotite and hornblende — is different from that of the Grimstad granite, where albite and alkali feldspar are late products encasing partly resorbed femic minerals and oligoclase.

In the light of experimental studies Tuttle and Bowen (1958) point out that rapakivi textures may develop in magmas somewhat richer in potassium than the "average" granite when the liquidus range is depressed below the feldspar miscibility gap as a result of enhanced water pressure. The experimental data on the alkali feldspar phase diagram support the idea that the mineral equilibrium of the Grimstad granite were fixed at a late stage of the petrogenesis since coexistence of An_8 and K-feldspar corresponds to late-magmatic, perhaps even hydrothermal temperatures.

It should be borne in mind, however, that the chemical system of the Grimstad granite is not the chemical system of the alkali feldspar diagram. The occurrence of epidote and biotite in the helsinkite variety and the coexistence of sericitized oligoclase and fresh albite shows that the granite may not have been completely melted at the time of its emplacement. Furthermore, the Grimstad granite is not particularly potassium rich and the existing theories on the formation of rapakivi plutons can not be directly applied to the genesis of the Grimstad granite. But the many mineralogical similarities with rapakivi plutons suggest that important common features of petrogenesis may exist. According to Laurén (1968) gravity measurements show that Finnish rapakivi plutons are bodies of great vertical extent. From the chemical analyses it is obvious that the Grimstad granite is not an eutectoid granite in the sense of Fischer (1951). Von Platen (1965) has demonstrated, however, that a fixed chemical composition cannot be assigned to an eutectoid composition because this is dependent on the An content of the plagioclase in the rock supplying the partial melt.

From our study of the minerals we are inclined to consider pyroxene, amphibole, brown biotite, and plagioclase of the compositional range An_{20-35} as unstable during the later stage of the emplacement, perhaps even during the earlier stages. Furthermore, the granite seems to have consisted of two essentially different components: a solid phase consisting of individual crystals or small clusters of crystals, and the granite melt itself. It is the solid components which are responsible for deviations from eutectoid composition. Representatives of the eutectoid melt can presumably be found among the aplitic dikes and possibly also the fine-grained granites, where acid plagioclase of albitic composition dominates, together with almost non-perthitic alkali feldspar.

The melt itself has, therefore, acted as a conveying phase for intense ion exchanges and as a lubricating medium that lowered the viscosity and permitted the rise of the magma by buoyancy. From the widespread occurrence of fluorite in the granite we think that the melt must have had a certain amount of dissolved HF which would also contribute to lowering its liquidus temperature and increasing its action as a chemical solvent.

It seems reasonable to suggest that, if the chemical variations within the granite have a direct relation to the chemical variation of the rocks from which the magma was derived, these variation trends would have been destroyed when the magma was rising through the crust. The rise would favour formation of concentric structures as demonstrated experimentally by Ramberg (1967). It is impossible to relate the chemical trends of the Grimstad granite to such an extent as was demonstrated by Whitten (1957; 1961 a; 1962 b). The trends invariably show concentric patterns, not cross-cutting lamellar ones. We, therefore, think that the shape of the trend surfaces show that the chemical variation pattern is primarily a result of the mode of emplacement combined with the process of assimilation of basic rocks in the central part of the granite.

We are inclined to think of the large area of monzonite in the central part of the granite as a more basic layer that has been brought up together with the magma. The numerous aplitic dikes in this area would then suggest mobilization of a granitic melt at depth which then dissected the solid and hence more competent rock that now occurs as the included monzonite. The diffuse borders of the monzonite would be the result of metasomatic action of the granite magma. The sharp-edged dark inclusions occurring in the agmatite zone and in some scattered areas elsewhere in the granite also represent pieces of country rocks, somewhat less well assimilated in the granite. The degree of assimilation may be read from their content of albite and fresh biotite or alkali feldspar.

Metasomatic processes seem to have influenced the overall chemical variation in the granite markedly. This is seen from a comparison between the 137 and the 122 trend surfaces for several elements. In earlier granite literature the distance of migration of elements has been the subject of much discussion. It has been argued that diffusion through crystalline bodies is very slow, and from laboratory investigations it can be concluded that matter is not transported through dry crystals even on a geological time scale. However, Orville (1962) demonstrated that small quantities of material can be transported in intergranular hydrous phases, even in short periods of time. In the Grimstad granite assimilation processes have been active over several hundreds of meters, and it seems reasonable to suggest that the granitic material has been introduced into very large blocks of basic rocks by means of a hydrous intergranular phase, the water possibly being supplied by the amphibolite itself.

From the material collected by us it has not been possible to establish in detail the selective migration of the granite components during the assimilation process, because even the fresh looking amphibolite inclusions turned out to be chemically altered and we have only a few samples that are exceptions to this. However, K-rich minerals, either K-feldspar or biotite — depending on the Fe-Mg concentration and possibly the water pressure — seem to be the first minerals to be formed, and the K-rich alkali feldspar porphyroblasts can be of considerable size.

In the classical French localities, granitization is examplified by growth of large porphyroblasts of alkali feldspar (dents de cheval) across sharp borders between granite and country rock, and this observation can be confirmed from numerous other localities. We apply the term granitization to the assimilation process responsible for the conversion of basic rocks into granites in the solid state. As seen from Table II the inclusions become enriched in alkalis as the granitization proceeds. This leads to formation of alkali feldspar and/or biotite.

Since there is no straightforward relation between total content of alkalis and content of alkali feldspar, granitization cannot be studied just by examination of the occurrence of alkali feldspar porphyroblasts. It is certainly true that granitization as such can be examplified by increase of alkali feldspar, in some cases as dents de cheval, but such cases are special since granitization may be followed by growth of biotite.

As the result of the present study, the petrogenesis may be summarized as follows:

The Grimstad granite is an intrusive magmatic granite. The magma was formed by anatexis and rose because of its reduced viscosity by buoyancy through the crust. Large blocks of country rocks were rotated by its emplacement and an extensive agmatite zone was formed. The magma probably consisted of a certain proportion of solid components, mainly basic oligoclase, amphibole, epidote, biotite, and pyroxene in variable amounts. The liquid component of the magma possibly had eutectoid composition, it crystallized to give coexisting albite and K-feldspar and is found both as interstitial material througout the granite and as aplitic dikes. All the chemical trend surfaces are of concentric nature and the chemical composition of the nearby country rocks has no significant influence on the shape of the trend surfaces of the granite. This indicates that the mode of intrusion and granitization in connection with the basic inclusions in the center of the granite had a major influence on the shape of the chemical trend surfaces of the Grimstad granite.

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APPENDIX

Sampling method, sample preparation, analytical methods

The sampling of the Grimstad granite was carried out according to a square grid with sides equal to 500 meters, the samples being taken in the grid corners (Figure 4). Other types of sampling plans were discussed, but since the granite is approximately circular, homogeneous and without any pronounced structural features, the square grid was found to be the most appropriate.

Of the 150 grid sample stations only 13 were eliminated due to lack of outcrops. Thus, 91 % of the planned grid point samples were collected. At every grid point where the normal granite occurred it served as a grid point sample, and macroscopically distinctive variants were sampled as supplementary specimens. At fifteen localities where normal granite did not occur, porphyritic or porphyroblastic varieties were taken as grid point samples.

The composition of the analyzed sample for any one grid point may not be exactly the same as that of the rock which it is supposed to represent. In other words it is important to know the sampling error, in this case how large a variation occurs within one locality in the normal granite. Therefore a series of 15 normal granite samples were collected at random in one outcrop near Fevik in the central part of the granite.

Another way of attacking this problem is to take two or more samples of the same rock type from each locality. The replicates may then be used to calculate an estimate of the variation within an outcrop. This is probably a statistically better sampling method, but since it meant doubling the number of samples and thereby the analytical work, which was beyond our laboratory capacity at that time, this method of sampling was not attempted.

The sample size was usually between 2 and 3 kgs. Great care was taken to ensure fresh samples, weathered samples or weathered parts of samples were discarded. The outcrops are mostly so fresh that drilling was not necessary.

In addition to the 137 grid point samples, 87 samples were collected for special investigations. These samples are amphibolites, gneisses and quartzites from the country rocks, basic inclusions from the agmatite border zone, samples from the monzonitic and porphyroblastic (quartz)-monzonitic rock types within the granite, and the above mentioned series of 15 normal granite samples from one single outcrop.

The samples were cut into three pieces using a diamond saw. One part was used for modal analysis, another was kept as a hand specimen and the third and largest one was crushed for analysis.

Preparation for modal analysis.

The slab to be used for modal analysis was etched with conc. HF and dyed with a saturated solution of fresh sodiumcobaltnitrite. The method is described in Bailey and Stevens (1960). The slab was then counted with a special slab point counter used in conjunction with a binocular microscope (Smithson, 1963 c). For each slab a minimum of 1000 points were counted over an area not less than 10 x 10 cm^2.

Preparation for X-ray fluorescence analysis.

Bulk rock. The sample (approximately 1 kg) was crushed in a jaw crusher and split repeatedly to give ca. 100 grams. This portion was then fine crushed for 3 minutes in a steel ring mill. The iron contamination in this mill is considerable, approximately 0.3 % Fe_2O_3 is added during a 3 minutes run. There is, howevei, no reason to assume variations in the contamination from sample to sample. The effect will therefore mainly be an overall increase in the Fe_2O_3 content and will not influence the comparison between samples.

Pellets for X-ray fluorescence analysis were made in a Millen mounting press under a pressure of 5500 lbs/inch^2. The pellets were made from ca. 2 grams of fine crushed rock powder. Polyvinylchloride was first used as coating material, but during the analysis it was found that the PVC gave off small amounts of chlorine under vacuum, which caused rusting of the steel specimen holder of the X-ray spectrograph. For later work boric acid was therefore used instead of PVC.

Feldspars. The amount of material available was limited and the X-ray fluorescence determinations were therefore made on loose powder fine crushed by hand in an agat mortar.

Mineral separation methods.

22 samples from two profiles across the granite were subjected to mineral separation for chemical and structural investigation of the feldspars.

The samples were ground to approximately 70 mesh in a plate crusher with repeated sieving, washed and separated by a Frantz isodynamic magnetic separator into three fractions. The magnetite and biotite fractions were not treated any further.

The third fraction containing the light minerals quartz, alkali feldspar and plagioclase, was subjected to flotation techniques using HF and dodecylamine to separate quartz from the feldspars. The feldspar mixture was then washed with alcohol to remove the dodecylamine and separated into plagioclase and alkali feldspar fractions by means of heavy liquid separation in acetylene tetrabromide.

The plagioclases gave 10—15 fractions, all of which were examined in immersion liquids under the microscope for impurities. The first apparently pure plagioclase fraction was chosen as material for analysis. X-ray Guinier powder exposures showed, however, that there were still small amounts of quartz present. To obtain a more accurate determination of the quartz content the Guinier films were measured photometrically against plagioclase-quartz standards. The chemical data of Table VIII b are corrected for quartz contamination of the plagioclase fractions.

The alkali feldspar fraction was removed as one fraction to avoid separation of the perthite into K-feldspar groundmass and albite component. It is important, particularly for a possible use of the chemical data for two-feldspar thermometry, to obtain a fraction representing the alkali feldspar before the exsolution of albite lamellae.

Analytical methods.

The elements analyzed and the instruments used are shown in tabular form below:

Instruments	Elements	Standards
Philips vacuum X-ray fluorescence spectrograph	Si, Ti, Al, Fe_{tot}, Mg, Ca, K, P Rb, Sr	International and house standards. A list is given below.
Beckman flame photometer, model B	Na in bulk rocks	Synthetic standards

Instruments	Elements	Standards
Beckman atomic absorption spectrophotometer, model DB	Mg in concentrations higher than 2 %	Synthetic standards
Intertechnique 400-channel analyzer with NaI (Tl) crystal (neutron activation analysis)	Na in feldspars	International rock standards G-1 and GSP-1
Gravimetric chemical analysis	Fe^{++}	Titration with $K_2Cr_2O_7$

The following rock standards in different combinations were used to determine the standard curves:

G-1 W-1 AGV-1 GSP-1 G-2 PCC-1	U.S. Geological Survey
T-1	Geological Survey, Tanzania
GR	C.R.P.G., Nancy, France
Milford granite	U.S. Bureau of Standards
Biotite granite Nordmarkite Gabbro Amphibolite Diabase Antophyllite-cordierite rock Nepheline syenite	House standards from Mineralogisk-Geologisk Museum, Oslo

The neutron activation analysis has been performed according to the method described by Brunfelt and Steinnes (1966).

Precision and accuracy of the analytical methods.

The following calculations have been performed in order to obtain some measure of the precision and accuracy of the methods compared to variation within an outcrop:

1) The precision for each element given as standard deviation of a series of 7 parallels of one sample. The results are given in Table XI.
2) A measure of the scatter of points around the standard curve. This problem is well known to the geochemist working with rock standards. As is often said, the analyses can be no better than the standards on which they are based. We therefore feel that a quantitative measure of the "goodness of fit" for the different standard curves ranks equal in importance with a measure of the precision of the methods used. We have chosen a standard statistical method for calculation of the variation around the standard curve. The formulas are given in Crow, Davis and Maxfield (1960). The results given in Table XI show the relative standard error of the regression coefficient b (slope of the curve) for each standard curve.
3) The variation within an outcrop. The results given in Table XI show the standard deviation of a series of 15 normal granite samples collected at random at one locality near Fevik.

From a comparison between the precision and the variation within an outcrop it seems clear that the precision for most of the elements is good enough to trace significant variations within the granite body. Exceptions are MgO, Al_2O_3 and Na_2O. For the two last elements the precision in itself is relatively good, but since the corresponding variation within an outcrop is practically the same one must be careful in interpreting chemical variations in these two elements.

MgO and Al_2O_3 also distinguish themselves by their standard curves which show a high degree of inaccuracy.

In the case of MgO, the contents are low in the normal granite (usually 1 % or less). This means that the lack of precision and accuracy will be of little importance in the chemical analyses. Samples with a MgO content higher than 2 % have been reanalyzed by atomic absorption.

Table II. Slab modal analyses of the different rock types within the granite.

Rock type	No. of samples	Modal minerals	Mean x	Stand. deviation s	Variance s^2	Stand. error of the mean s_x	Range of valus w
Normal granite	114	Q	26.0	4.1	16.6	0.4	13.3—37.9
		Alk.fsp.	39.8	5.7	32.2	0.5	23.1—53.2
		Plg	28.1	4.1	17.1	0.4	18.5—44.5
		Bi	4.8	1.5	2.1	0.1	0.9—10.5
		Acc	1.3	0.6	0.3	0.1	0.1— 3.2
Medium grained granite	14	Q	27.5	5.1	25.9	1.4	22.3—40.4
		Alk.fsp.	35.4	5.3	28.3	1.4	19.9—40.8
		Plg	30.3	3.0	8.7	0.8	25.3—36.9
		Bi	5.8	2.2	4.6	0.6	1.1— 8.7
		Acc	1.0	0.6	0.4	0.2	0.1— 2.0
Fine grained granite	8	Q	25.3	3.6	11.2	1.2	19.7—30.2
		Alk.fsp.	37.3	8.0	64.5	2.9	17.6—40.3
		Plg	32.4	11.9	140.4	4.2	24.9—60.8
		Bi	4.0	1.4	2.0	0.5	1.8— 8.3
		Acc	1.9	0.8	0.6	0.3	0.1— 2.2
Aplite	4	Q	34.1	1.6	2.6	0.8	32.4—36.4
		Alk.fsp.	41.9	3.5	12.1	1.7	37.4—50.6
		Plg	20.1	25.1	26.2	2.6	8.2—24.6
		Bi	2.0	2.4	6.2	1.2	1.2— 6.6
		Acc	1.9	1.7	2.9	0.9	0.6— 4.9
Porphyritic granite	9	Q	23.3	3.5	12.3	1.2	18.0—30.7
		Alk.fsp.	39.0	2.9	8.4	1.5	34.8—43.8
		Plg	30.5	3.9	14.9	1.3	27.6—38.3
		Bi	5.7	2.2	4.6	0.7	2.1— 9.1
		Acc	1.5	1.3	1.6	0.4	0.6— 4.3
Porphyroblastic (quartz)-monzonite	4	Q	18.9	3.7	13.9	1.9	14.6—23.7
		Alk.fsp.	29.6	3.6	12.9	1.8	34.3—43.8
		Plg	36.6	3.0	8.8	1.5	33.7—39.5
		Bi/Hbl	11.6	3.1	9.9	1.6	7.7—15.2
		Acc	3.3	1.9	3.7	1.0	0.9— 5.4
Monzonite	12	Q	14.5	5.2	26.5	1.5	8.3—17.4
		Alk.fsp.	23.4	7.0	49.6	2.0	10.8—34.9
		Plg	37.3	6.2	38.8	1.8	28.8—44.6
		Bi/Hbl	22.1	5.5	29.7	1.6	15.0—33.8
		Acc	3.7	1.3	1.6	0.4	2.0— 4.8

Table III. RΔ values in monzonites and (q)-porphyroblastic monzonites.

Sample number	Max. Δ value	RΔ
K 11	0.90	—
R 10—1b	not possible to determine	X
R 12	0.80	X
S 14—5	0.77	X
S 14—7	0.90	X
S 14—10	0.75	X
S 14—14	0.85	X
T 14—8	0.87	X

Table IV. Modal mineral variation within an outcrop (0 16).

No. of samples	Modal minerals	Mean $\bar{x}$	Stand. deviation s	Variance s^2	Stand. error of the mean $s_{\bar{x}}$	Range of values w
6*	Q	26.5	2.7	7.5	1.1	23.8—30.7
	Alk.fsp.	37.3	3.0	9.0	1.2	34.3—43.3
	Plg	29.7	2.8	7.7	1.1	25.2—32.6
	Bi	5.3	0.9	0.8	0.4	4.2— 6.4
	Acc	1.2	0.8	0.6	0.3	0.5— 2.9
	C.I.	6.5	0.9	0.8	0.4	5.1— 7.4

* Each sample is counted (1000 points or more) three times by different observers.

Table V. A pooled estimate of the mean precision of the slab modal analyses.

No. of samples	No. of analyses	Modal minerals	Mean $\bar{x}$	Stand. deviation s_p	Variance s^2_p	Stand. error of the mean $s_{\bar{x}}$	Range of values w
11	34	Q	24.0	1.8	3.4	0.5	14.6—30.7
		Alk.fsp.	38.4	2.6	6.9	0.8	28.7—45.3
		Plg	29.9	1.7	3.0	0.5	25.9—38.7
		Bi	6.2	0.7	0.5	0.2	3.2—15.2
		Acc	1.5	0.6	0.4	0.2	1.2— 2.8
		C.I.	7.7	0.7	0.5	0.2	4.2—18.0

Table VI. Precision of the mesonorm analyses.

No. of analyses	Mesonorm minerals	Mean x	Stand. deviation s	Variance s^2	Stand. error of the mean s_x	Range of values w
7	Q	24.5	0.6	0.3	0.2	23.8—25.4
	C	0.6	0.2	0.04	0.1	0.3— 0.8
	Or	29.5	0.2	0.03	0.1	29.3—29.7
	Ab	31.2	0.6	0.3	0.2	30.4—32.1
	An	5.1	0.1	0.002	0.02	5.1— 5.2
	Bi	6.5	0.4	0.2	0.2	5.6— 6.8
	Sph	0.9	0.02	0.0004	0.01	
	Mt	1.5	0.2	0.03	0.01	1.4— 1.8
	Ap	0.3	0.01	0.0001	0.004	
	C.I.	9.1	0.3	0.1	0.1	8.6— 9.3

Table VII. Mesonormative mineral variation within an outcrop (0 16).

No. of samples	Mesonorm minerals	Mean x	Stand. deviation s	Variance s^2	Stand. error of the mean s_x	Range of values w
15	Q	24.2	1.0	1.0	0.3	22.9—26.0
	C	0.5	0.2	0.04	0.1	0.1— 0.8
	Or	30.3	1.4	1.9	0.4	28.3—32.8
	Ab	31.2	0.8	0.6	0.2	30.4—32.5
	An	5.6	0.7	0.4	0.2	4.7— 6.7
	Bi	5.3	0.5	0.2	0.1	4.6— 6.6
	Sph	0.9	0.1	0.002	0.01	0.8— 1.0
	Mt	1.8	0.2	0.03	0.04	1.4— 2.0
	Ap	0.2	0.04	0.002	0.01	0.2— 0.3
	C.I.	8.2	0.5	0.2	0.1	7.6— 9.2

Table VIII a. Chemical analyses of the alkali feldspars.

Rock type	Sample number	Na_2O	K_2O	CaO	Rb	Sr	K/Rb	Ab	Or	An
		weight %			ppm			molecular %		
Normal granite	U 9-2	2.1	13.0	0.1	450	621	240	19.6	79.9	0.5
	T 10	2.3	12.7	0.2	368	679	285	21.4	77.6	1.0
	S 11	2.0	13.2	0.2	592	484	186	18.5	80.5	1.0
	O 14	1.6	13.5	0.1	826	438	136	15.2	84.3	0.5
	N 15	1.9	12.7	0.2	578	526	182	18.3	80.6	1.1
	M 16	1.7	13.4	0.1	625	481	178	16.1	83.4	0.1
	L 17	1.7	13.8	0.1	559	420	204	15.7	83.8	0.7
	K 18	1.9	13.4	0.2	523	570	212	17.6	81.4	1.0
	I 18-3	2.6	12.1	0.3	295	587	342	24.2	74.2	1.6
	L 8	1.6	13.5	0.9	503	603	223	14.6	80.9	4.5
	M 9	2.2	12.5	0.1	472	756	220	21.0	78.5	0.5
	N 10	1.5	13.6	0.2	580	644	195	14.2	84.8	1.0
	P 12	2.0	12.6	0.1	444	446	236	19.3	80.2	0.5
	Q 13	1.6	13.6	0.1	682	165	266	15.1	84.4	0.5
	R 14	1.5	13.4	0.1	529	462	268	14.5	85.0	0.5
	U 17	2.4	12.3	0.2	543	594	188	22.6	76.3	1.1
	V 18	1.9	13.2	0.2	654	446	164	18.0	81.0	1.0
Medium grained granite	K 7	1.1	13.6	0.1	338	650	334	10.9	88.6	0.5
Fine grained granite	R14fg	1.5	13.8	0.1	737	187	156	14.1	85.4	0.5
Aplite	V 8-1	1.0	14.4	0.1	1419	81	85	9.5	90.0	0.5
Porphyrobl. (q)-monzonite	S 14-5	2.1	12.0	0.3	178	1784	562	20.7	77.7	1.6
Monzonite	R 12	2.6	11.5	0.4	85	2122	1118	25.0	72.9	2.1

Table VIII b. Chemical analyses of the plagioclase feldspars.

Rock type	Sample number	Na_2O	K_2O	CaO	Rb	Sr	Ab	Or	An
		weight %			ppm		molecular %		
Normal granite	U 9-2	9.1	1.3	1.8	92	1093	88.1	7.8	9.1
	T 10	8.4	1.8	1.7	100	712	79.8	11.3	8.9
	S 11	8.9	1.0	2.0	50	1046	83.5	6.2	10.4
	O 14	9.0	1.4	1.4	169	1032	84.2	8.6	7.2
	N 15	8.7	1.3	2.3	130	981	80.4	7.9	11.7
	M 16	8.5	1.2	1.7	151	982	83.1	7.7	9.2
	L 17	9.4	1.1	1.5	77	925	85.8	6.6	7.6
	K 18	8.1	1.0	2.4	69	1245	85.5	6.5	13.2
	I 18-3	8.3	1.8	2.6	74	997	76.0	10.8	13.2
	L 8	8.1	1.3	1.8	75	660	81.4	18.6	10.0
	M 9	9.1	2.2	0.8	182	805	82.8	13.2	4.0
	N 10	9.2	1.8	1.7	82	1095	81.3	10.4	8.3
	P 12	9.2	1.9	1.1	99	746	83.2	11.3	5.5
	Q 13	9.4	1.3	0.8	107	424	87.9	8.0	4.2
	R 14	8.4	1.6	1.4	110	793	82.1	10.3	7.6
	U 17	8.5	2.1	1.7	182	767	78.5	12.8	8.7
	V 11	9.3	2.0	1.3	122	615	82.1	11.6	6.3
Medium grained granite	K 7	7.9	1.5	3.6	30	1168	72.6	9.1	18.3
Fine grained granite	R 14fg	9.3	1.5	1.0	141	456	85.8	9.1	5.1
Aplite	V 8-1	6.1	1.7	0.4	88	67	82.0	15.0	3.0
Porphyrobl. (q)-monzonite	S 14-5	6.9	2.4	3.1	56	1495	67.7	15.5	16.8
Monzonite	R 12	6.8	3.4	3.2	114	3755	62.9	20.7	16.4

Table IX. Rb and Sr in bulk rock.

	ppm Rb[1]	ppm Sr[2]
Normal granite (average of 17)	226	460
Medium grained granite (K 7)	159	600
Fine grained granite (R 14 fg)	287	200
Aplite (V 8-1)	449	50
Monzonites (average of 2)	62	1480

[1] Analyzed by X-ray fluoresence.

[2] Calculated from feldspar analyses and mode.

Table X. K, Rb and K/Rb in bulk rock.

Rock type	Sample number	% K	ppm Rb	K/Rb
Normal granite	U 9-2	3.2	172	186
	T 10	5.0	172	290
	S 11	4.2	198	212
	O 14	5.5	372	147
	W 15	4.2	230	182
	M 16	4.6	262	175
	L 17	4.6	244	188
	K 18	4.2	184	228
	I 18-3	4.6	140	328
	L 8	4.6	205	224
	M 9	5.1	204	250
	N 10	4.6	254	181
	P 12	4.5	225	200
	Q 13	4.4	274	160
	R 14	4.2	197	213
	U 17	4.7	234	200
	V 18	4.4	280	157
Medium grained granite	K 7	4.7	159	295
Fine grained granite	R 14 fg	5.3	287	184
Aplite	V 8-1	4.4	449	97
Monzonites and porphyroblastic (q)-monzonites	R 12	2.8	29	965
	K 12-1b	2.9	52	557
	K 14-1	2.9	76	381
	S 14-3	2.4	55	436
	S 14-5	3.7	94	393
	S 14-10	3.1	61	508
	S 14-14	4.4	143	307
	R 10-1b	2.9	54	537

Rock type	Sample number	% K	ppm Rb	K/Rb
Acid and intermediate gneisses	H 18-1	0.8	35	228
	I 7-1	4.6	167	275
	I 19	0.9	54	166
	K 6	3.3	187	176
	K 6-2	4.6	216	212
	L 4-1	1.8	224	80
	S 7	1.9	96	197
Amphibolitic inclusions	T 8-1a	2.7	93	290
	T 8-2a	3.1	124	250
	T 8-3	4.4	172	255
	T 8-4	3.0	100	300
	T 8-5	2.7	51	529
	T 8-6	2.2	145	151
	T 8-7	3.2	63	507
	T 8-8	3.4	100	340
Amphibolites	C 21-1	0.5	3	1666
	D 20-1	0.9	20	450
	F 9	1.4	22	636
	F 12	3.2	90	355
	F 19-1	0.5	4	1256
	G 18-1	0.6	11	545
	H 15	1.7	29	586

Table XI.

	Analytical precision Standard deviation			Variation around the std.curve	Variation within outcrop. Std. deviation	
	Weight % Mean	Abs.	Rel. %	Rel.std.er. %	Abs.	Rel. %
SiO_2	69.92	0.42	0.6	1.0	0.82	1.1
Al_2O_3	14.11	0.16	1.2	5.5	0.15	1.1
TiO_2	0.41	0.01	1.7	1.0	0.03	6.0
Fe_2O_3	2.95	0.02	0.7	2.7	0.17	5.7
FeO	1.80	0.04	2.2		0.15	10.0
MgO	1.10	0.06	5.0	6.2	0.07	6.2
CaO	1.47	0.01	0.5	1.4	0.13	9.0
Na_2O	3.44	0.07	2.1		0.07	2.1
K_2O	5.59	0.01	0.2	1.5	0.21	3.8
P_2O_5	0.13	0.004	3.1	1.7	0.01	6.2

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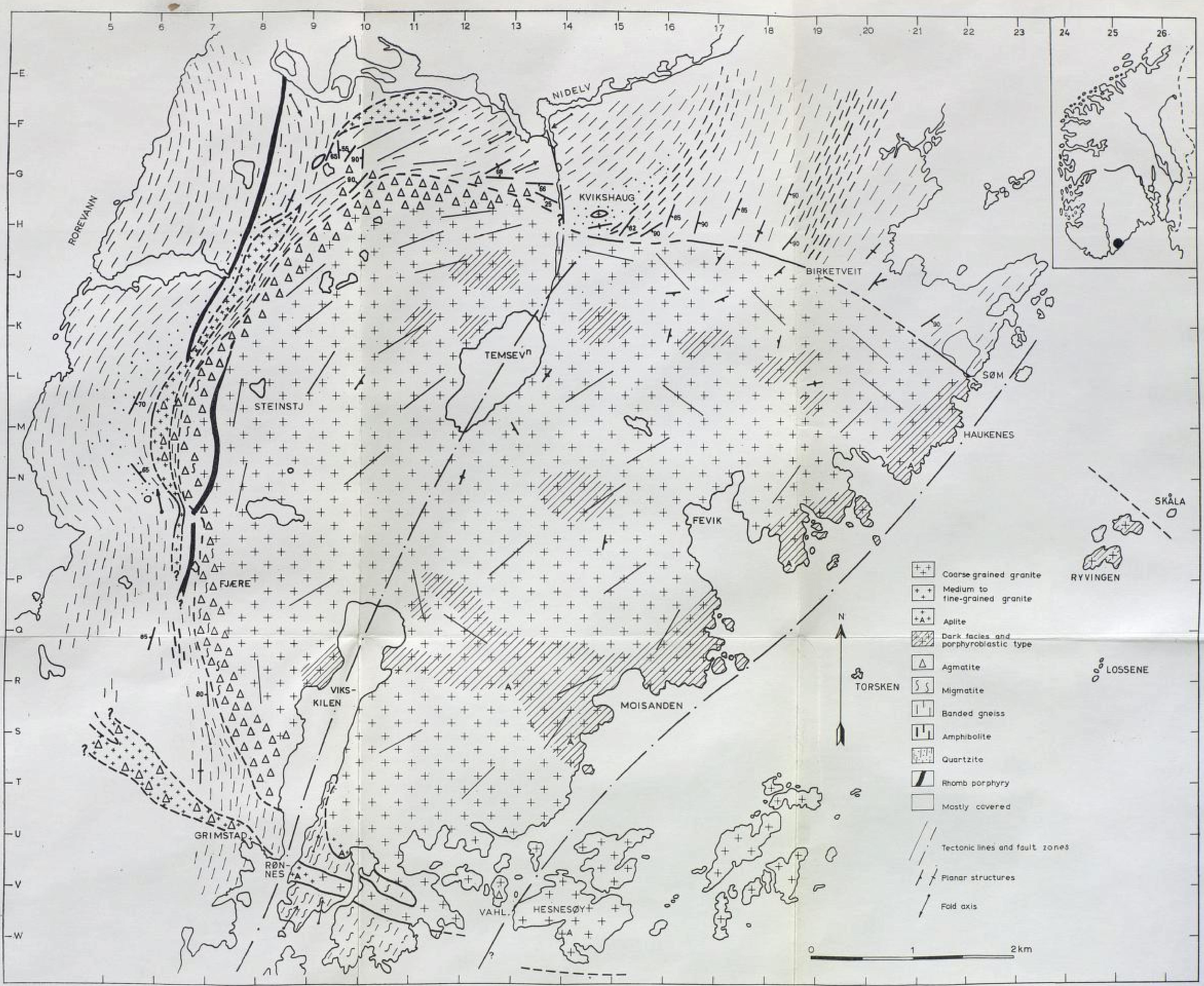

Figure 1. Geological map of the Grimstad granite. Location map inserted.